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HELMET MOUNTED EYE TRACKING FOR VIRTUAL PANORAMIC DISPLAY SYSTEMS — VOLUME II: EYE TRACKER SPECIFICATION AND DESIGN APPROACH (U)

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FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
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The virtual cockpit concept being developed by the Air Force will require a helmet mounted eye tracker to be integrated with a helmet mounted virtual panoramic display (VPD). Eye tracker measurements will be used with prototype systems to assist in candidate display evaluation. Operationally, eye tracking will be used for eye controlled switch selection, cueing, eye slaved aiming, and pilot state monitoring.

Current eye tracking technology is reviewed in Volume I of this report. Relevant physiological considerations and the performance requirements implied by each of the above VPD tasks are thoroughly reviewed in Volume II.

A pupil center to corneal reflex technique is proposed as the most suitable technique for a VPD eye tracker. The need for robustness and dependability in the virtual cockpit

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application can best be met by using a full two dimensional solid state array detector and a system that makes the complete image available to a digital processor.

Performance goals have been proposed that are feasible and will satisfy the virtual cockpit task requirements. An eye tracker design approach and prototype development plan have been outlined to meet these goals, including as examples an analysis of possible optical paths for integration with the off aperture and dual mirror VPD designs.

PREFACE

The goal of this work was to explore integration of an eye line-of-gaze measurement system (eye tracker) with a helmet-mounted, virtual panoramic display (VPD). The report is presented in two volumes. Volume I is a review of current eye tracking technology, while Volume II directly addresses the VPD application requirements.

The work reported on herein was performed under Contract Number F33615-87-C-0542 for a Phase I, FY87 effort in the Small Business Innovation Research Program. Ms Gloria Calhoun of the Armstrong Aerospace Medical Research Laboratory (AAMRL), Human Engineering Division, Visual Display Systems Branch, with Ms Gloria Calhoun serving as technical monitor. The work was done primarily at Applied Science Laboratories (ASL) in Waltham, Massachusetts, but also includes a brief set of tests performed at AAMRL Wright-Patterson Air Force Base, Ohio.

Important contributions were made by Professor Laurence R. Young, principal consultant to ASL and director of the MIT Man-Vehicle Laboratory, Professor Steven Benton, consultant to ASL and director of the Spatial Imaging Group at the MIT Media Laboratory, and Jose Velez, ASL research scientist.

A great deal of support was also provided by several individuals at AAMRL who supplied information about Air Force goals and related display technology, participated in tests at AAMRL, generated feedback and suggestions, and served as editors. These people include Ms Gloria Calhoun, Lt German Valencia, Dr Brian Tsou, Mr Dean Kocian, Dr Herschel Self and Dr Wayne Martin.

The author is also grateful to Dr Hewitt D. Crane, of SRI International, and Mr Paul Weisman of Farrand Optical for their suggestions and helpful information.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES
(continued)

1.0 INTRODUCTION

To meet future operational needs, the Air Force is currently developing technology for a revolutionary crew station design, often referred to as the "Super Cockpit." Central to the program is the "virtual cockpit" concept in which information from many different sources is used to create a "virtual world" around the pilot. An overall block diagram of the system is shown in figure 1.1. The "visual world" will be created by a helmet-mounted virtual panoramic display (VPD). Helmet position and orientation will be measured with a magnetic position detection system and, to function as envisioned, a helmet-mounted eye tracker must be included to measure eye line-of-gaze.

Eye tracker measurements will be used with prototype systems to assist in candidate display evaluation. Operationally, eye tracking will be used for eye-controlled switch selection, cueing, eye-slaved aiming, and pilot state monitoring. Each of these applications implies certain eye tracker performance requirements.

Current eye tracking technology has been reviewed in Volume I (Review of Current Eye Movement Measurement Technology). Eye tracker requirements and design for the VPD application are explored in this volume. After reviewing important physiological considerations and defining eye tracker performance measures, each virtual cockpit application is analyzed in terms of its eye tracker performance requirements.

Based on the information in the volume I review, the analysis of specific application requirements, and experience at Applied Science Laboratories, a pupil-to-corneal reflex approach is proposed as the most suitable technique for eye tracking on the VPD helmet. It is further recommended that a two-dimensional solid state array be used for the eye tracker detector, that an initial eye tracker design be monocular, and that the initial eye tracker have a 60 Hz update rate with future enhancements for faster update. Optical path, algorithm, and processor design approaches are discussed, and a prototype development project is outlined.

2.0 TYPES OF EYE MOVEMENT

2.1 Fixations and Saccades

During normal scanning of a visual scene, eye movement is characterized by a series of stops and very rapid jumps between stopping points. The stops, which normally last at least 200 msec, are called fixations, and it is during these fixations that most visual information is acquired and processed. The rapid jumps between fixation points are called saccades. Saccades are conjugate eye movements (both eyes move together) that can range from 1 to 50 degrees of visual angle, generally have durations of 30 to 120 msec, and achieve velocities as high as 400-600 deg/sec. Very little visual information is acquired during saccades, primarily because of the very fast motion of images across the retina, and an associated elevated visual threshold just prior to and during a saccade, i.e., visual image supression.

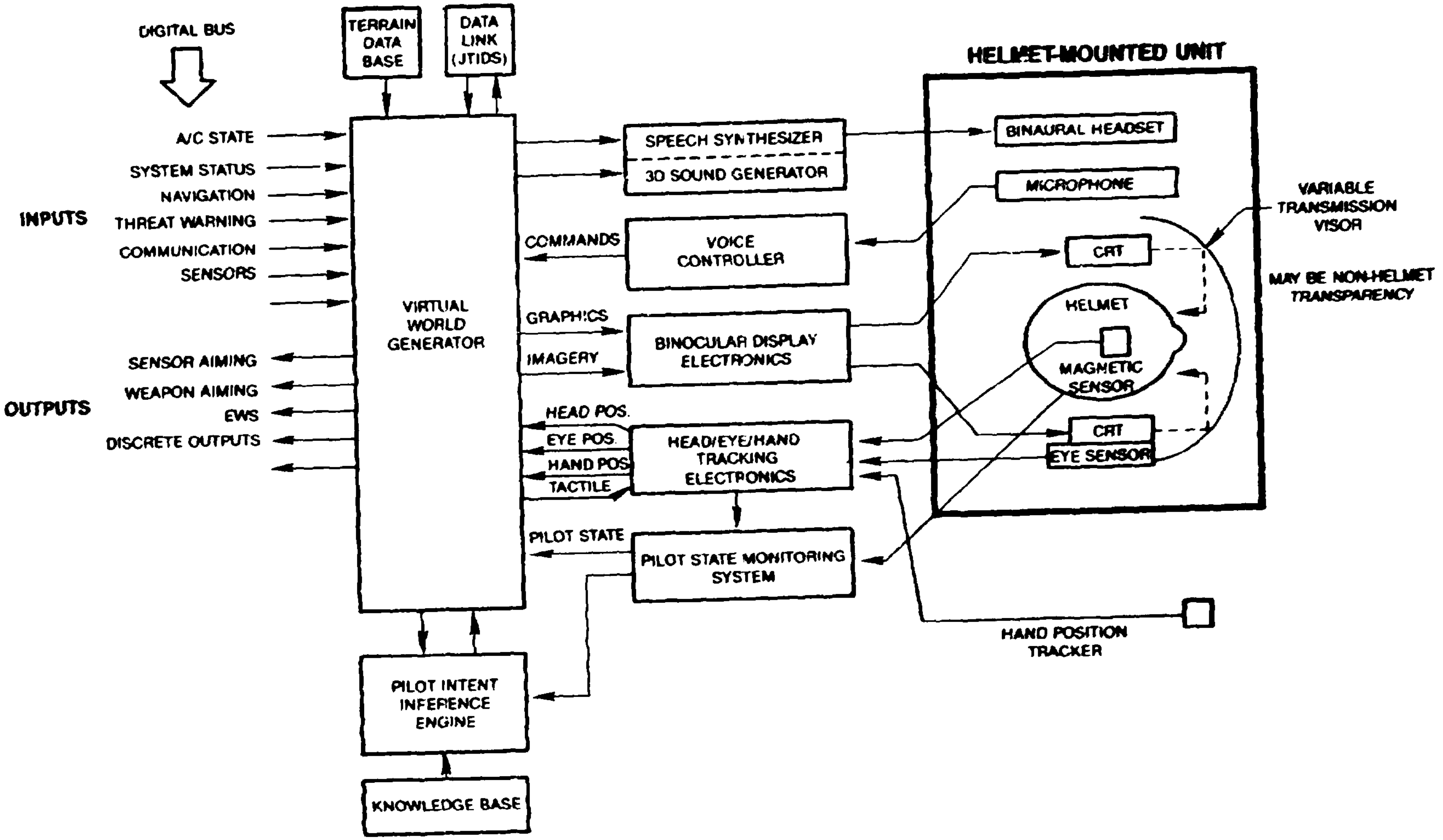

Figure 1.1 Super Cockpit System Hardware Block Diagram (ref. 1).

The eyes are not completely stationary during fixations, but exhibit a variety of small involuntary motions, usually of less than one degree of visual angle magnitude, called flicks, drifts, and tremor as described in section 2.2.

Smooth pursuit, compensatory eye movement, vergence, and nystagmus are nonsaccadic eye movements of relatively large magnitude.

2.2 Smooth Pursuit

The eye can smoothly track targets that are moving in the range of 1 to 30 degrees per second. Some, but not all, subjects can track targets up to about 75 degrees per second. These conjugate, slow tracking eye movements are usually called smooth pursuit and act to partially stabilize slowly moving targets on the retina. Slow, smooth eye movements cannot generally be executed voluntarily without the presence of a slowly moving target, however, voluntary control has been demonstrated after training.

2.3 Compensatory Eye Movement

Compensatory eye movements are conjugate eye motions which partially stabilize the visual field during either active or passive head or trunk motions. Such eye motions are involuntary and are in response to inertial information from the vestibular system and head motion information supplied by proprioceptive sensors in the neck.

2.4 Vergence

Vergence eye movements are nonconjugate eye movements needed to keep the visual scene in corresponding positions on both retinas. For example, if a person is fixating (foveating) a target point and the target begins moving closer to the person, the eyes must converge (both must rotate toward their nasal side) to maintain the image on corresponding parts of both foveas and thereby retain fusion of the image. Vergence eye movements have a range of about 15 degrees of visual angle and maximum velocities of about 10 degrees per second.

2.5 Nystagmus

Nystagmus is an involuntary sawtooth pattern of conjugate movement that occurs in response to apparent motion of the visual field (especially the peripheral field) or inertial rotation of the body. Each cycle is characterized by a "slow phase" in which the eyes move so as to stabilize the visual field on the retina, followed by a return saccadic jump or fast phase. The slow phase velocity and frequency of the pattern are related to the motion speed of the visual field or the speed of head rotation up to maximum velocities of about 100 deg/sec and nystagmus frequency of about 5 Hz. The amplitude is generally between 1 and 10 degrees of visual angle. Onset and changes in slow phase velocity of nystagmus are often similar to, although not identical to, a person's perception or sensation of angular rotation velocity. Pathological nystagmus, which can occur at certain gaze angles or head positions, in either eye, are important to clinical diagnosis in neurology, ophthalmology, and otolaryngology.

2.6 Flicks, Drifts, and Tremor

At least three types of small, involuntary eye motions commonly occur during eye fixations:

- Flicks or microsaccades are very rapid, involuntary, saccade-like motions of less than 1 degree which may be separated by as little as 30 msec, and tend to recenter images on the fovea.

- Drifts are very small, slow (on the order of 0.1 deg/sec), apparently random motions of the eye.

- Tremor is a tiny (less than 30 arc seconds) high frequency (30-150 Hz) eye vibration.

3.0 PHYSIOLOGICAL PERFORMANCE CONSIDERATIONS

3.1 Point-of-Regard

For most virtual cockpit eye tracker applications, the real quantity of interest is the pilot's point-of-regard. We want to know what the pilot is "looking at." The quantity actually measured by eye trackers is the direction of the eye's visual axis, relative to the environment, in other words, eyeball pointing direction.

Fixating a point in the visual field implies positioning the eye so that the image of that point falls on the fovea. The fovea is a small roughly disk-shaped area on the retina that offers the highest visual acuity and has a diameter corresponding to about 2 degrees of visual angle. It is possible to determine point-of-regard by measuring eyeball pointing direction only to the extent that people always put the target they want to "look at" on the same spot within the fovea.

People can consistently position stationary targets on the same retinal spot to within 1 degree of visual angle. Miniature eye movements, however, imply at least a minimum retinal dead zone. Slow drift typically results in 2 to 4 arc minutes of eye motion during fixation, but can approach 10 arc minutes or more of motion during long fixations. Microsaccades are typically about 5 arc minutes, but can sometimes be at least 0.5 degree. It has been shown that, under proper stimulus conditions, most people can voluntarily suppress microsaccades and maintain fixation with slow drift alone (ref. 2), but this requires conscious effort and does not represent normal scanning behavior.

Figure 3.1 shows examples of the area covered by the eye's visual axis during fixations. Figures 3.2, 3.3, and 3.4 show time recordings of eye position during fixations. Notice, from figure 3.4, that eye position deviation sometimes increases with fixation duration. All of these measurements were made using very accurate contact lens or corneal reflex tracking devices with the subject's head rigidly stabilized.

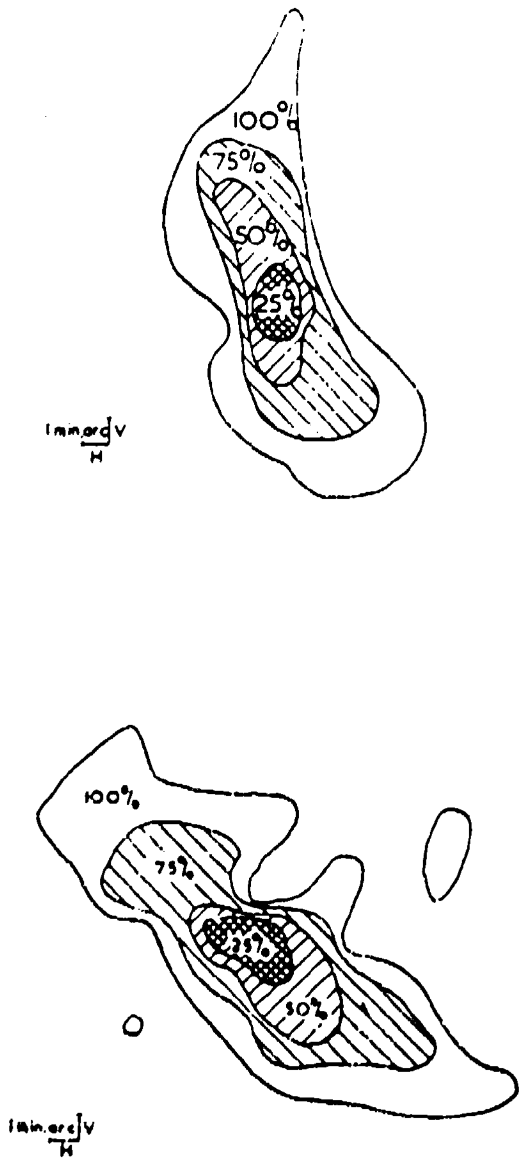

Figure 3.1 Area traversed by the visual axes of two different subjects during 10 second fixations; from Bennet-Clark (ref. 3). Contours enclose the densest 25%, 50%, and 75% of the record.

These data represent relatively long fixations. During normal scanning, fixations tend to average about 250 msec, however, the visual switch selection and cueing tasks associated with eye tracking in the virtual cockpit may sometimes involve fixations of 1 second or longer.

The data cited above deal with motion within a single fixation. It is also not clear that people fixate differently positioned targets with exactly the same retinal region, nor is it known if people position targets of different shape, contrast, luminance, contextual content, etc., at exactly the same area on the fovea.

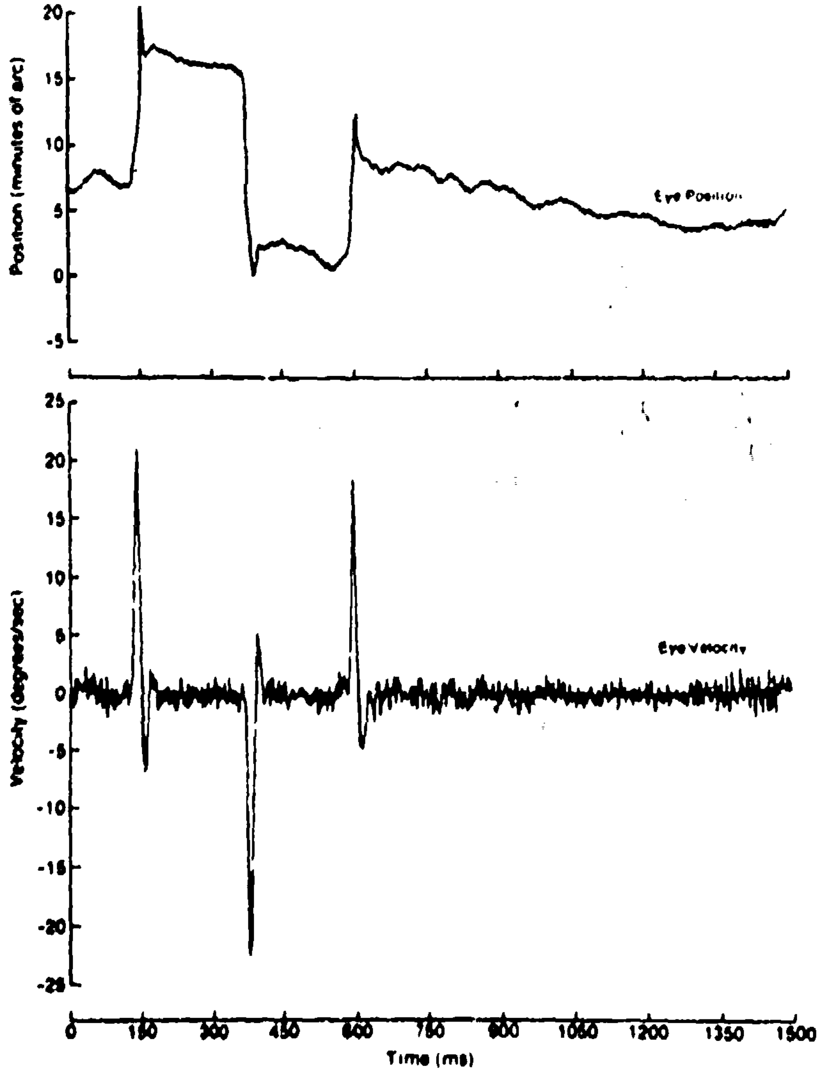

Figure 3.2 Typical horizontal eye position and velocity during a fixation; from Eiezenman, Frecker, and Hallet (ref. 4).

If a target already imaged on the fovea suddenly moves by a small amount, it has been shown that the probability of a corrective saccade occurring in a given amount of time decreases for decreasing amounts of target motion. Using such data, Young (ref. 7) postulated an effective foveal dead zone within which a target motion is not likely to produce a corrective saccade. He estimated this dead zone or "indifference threshold" to be approximately ± 0.3 degree visual angle.

It has also been shown by Bergin and Julez (ref. 8), Julez et al. (ref. 9) and Scinto (ref. 10) that, during a given fixation, focal attention can be directed to different areas within the fovea or, given sufficient acuity for the target of interest, even outside the fovea. Under normal conditions, if focal attention is sustained on an eccentric target, it will probably result in a saccade to center the target within about 150 msec to 1 sec, depending on distance from the foveal dead zone (ref. 11).

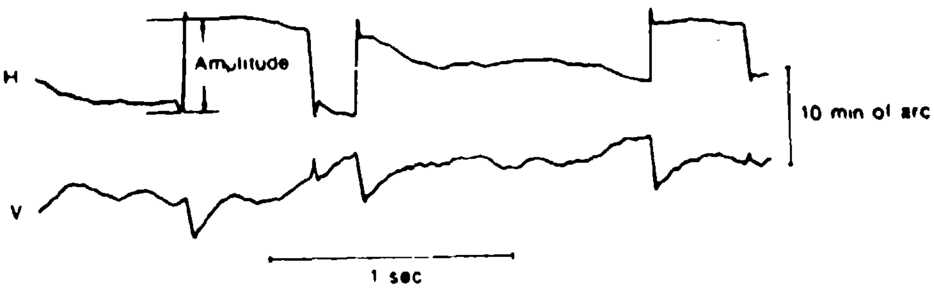

Figure 3.3 Typical horizontal and vertical eye motion during a fixation; from Gaarder (ref. 5).

We conclude that, in an operational or training environment, it does not seem reasonable to expect the eye visual axis to indicate point-of-regard consistently to within better than 0.3 degree visual angle. Any eye tracking error (error in determining the position of the visual axis) must, of course, be added to this.

Note that it is possible for people to consistently perform visual aiming tasks with far better accuracy than 0.3 degree. This is because aiming tasks usually do not require positioning a target at a certain point on the retina, but rather determining the relative alignment of two or more elements in the visual field.

3.2 Smooth Pursuit

Aiming and target designation will be important eye tracker applications in the virtual cockpit and will often involve targets that are moving across the visual field. The eye can smoothly track targets up to about 30 deg/sec, but with somewhat less accuracy than when fixating stationary targets.

People are usually unable to precisely match target velocity at even very slow target speeds and, as target speed increases, tracking errors tend to be periodically corrected with catch up saccades (ref. 12). At target speeds greater than 30 deg/sec, smooth tracking usually degenerates to a series of saccades, although some people can smoothly follow up to 75 deg/sec.

The pursuit system is quite nonlinear and smooth pursuit dynamics vary considerably, depending on target dynamics, target predictability, and other factors. In general, the pursuit system has low pass characteristics, with a corner frequency on the order of 1.5 Hz for

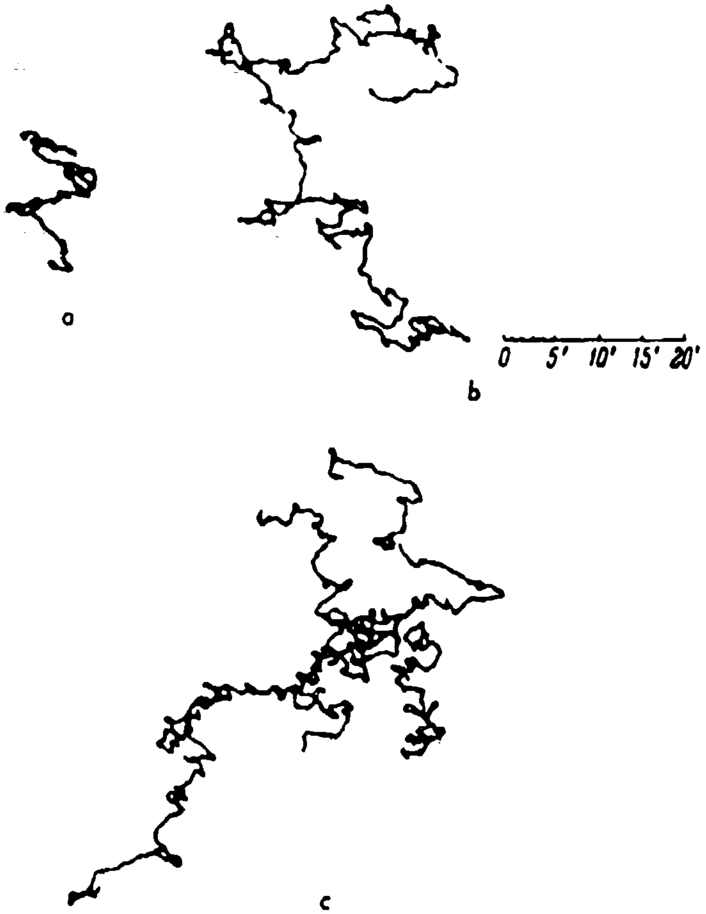

Figure 3.4 Eye position traces during 10 second (a), 30 second (b), and 1 minute (c) fixations; from Yarbus (ref. 6).

predictable targets and 1.0 Hz for unpredictable targets. As the spectral content of the target motion increases, pursuit system lag tends to increase (ref. 13 and 14). There is a latency of about 130 msec before the eye begins to track a moving target. If the target has a low luminance or low contrast, the latency will be greater. If the onset of target motion is predictable, this latency is reduced and, in fact, there may even be anticipatory smooth pursuit before target motion begins, or changes speed or direction (ref. 15 and 16).

A typical smooth tracking response is shown in figure 3.5. Unfortunately, smooth tracking data are usually presented in the literature in terms of velocity error and frequency response characteristics, and not in terms of retinal error. This information cannot easily be used to deduce position errors. We can estimate, however, that smooth pursuit of targets moving at over 10 deg/sec may lead to retinal eccentricity (target distance from foveal center) of 1 degree or more at least some of the time. A more accurate estimate will require further research.

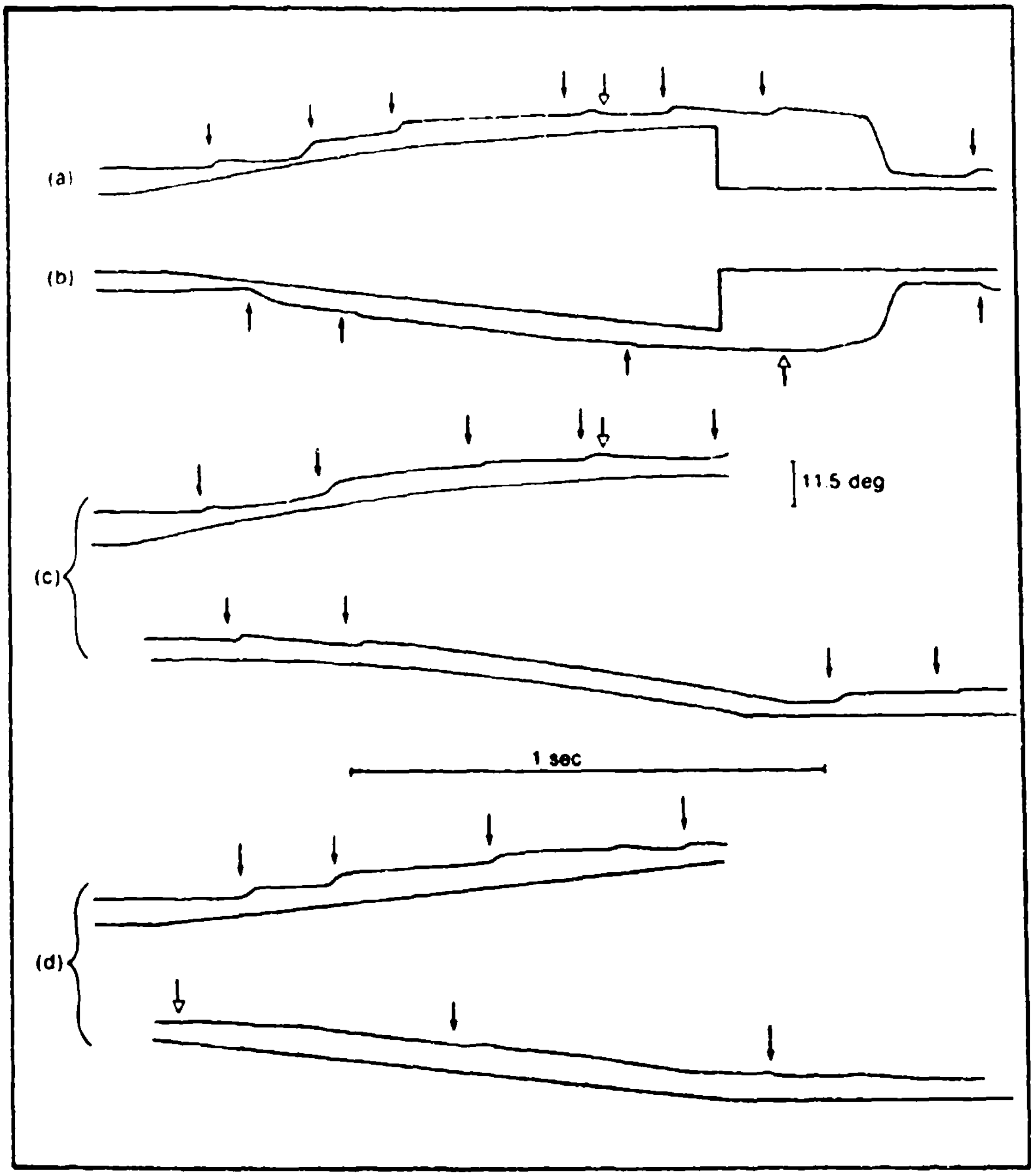

Figure 3.5 Horizontal smooth pursuit eye movements with eye position traces displaced 5.7 degrees above stimulus traces for clarity, from Hallett (ref. 12) after Lightstone (ref. 17). Initial velocity of ramp and sinusoid stimuli are 12 and 18 deg/sec respectively. Solid arrows show catch-up saccades and open arrows show velocity reversal points.

3.3 Range

The range over which people foveate (the range of eye motion) is about ±50 degrees horizontally and about +40 degrees, -60 degrees

vertically with respect to the head (ref. 18). There may be some tendency to foveate less accurately near the peripheries of this field than in the more central regions and maintainance of eccentric eye positions begins to become uncomfortable beyond about 40 degrees. The instantaneous ambinocular field-of-view (area that can be seen by either eye) with head and eyes fixed in a central position is about ±95 degrees horizontally and about +45 degrees, -65 degrees vertically. The vertical field asymmetry is due to obstruction from the orbital arch above the eye. The total ambinocular field-of-view with respect to the head is about ±165 degrees horizontally and +66, -82 degrees vertically (ref. 19).

3.4 Pupil Diameter

Pupil diameter varies over the population and responds to a multitude of physical and psychological stimuli. Full pupil diameter range is from about 2 mm to 10 mm. The most significant and predictable influence on pupil diameter is luminance of the visual field. Figure 3.6 shows the typical relation between uniform visual field luminance and pupil diameter. When steady state luminance is over 1000 mL (daylight conditions), pupil diameter values between 2 and 3 mm can usually be expected. Retinal adaptation to ambient illumination tends to return the pupil diameter toward its middle range.

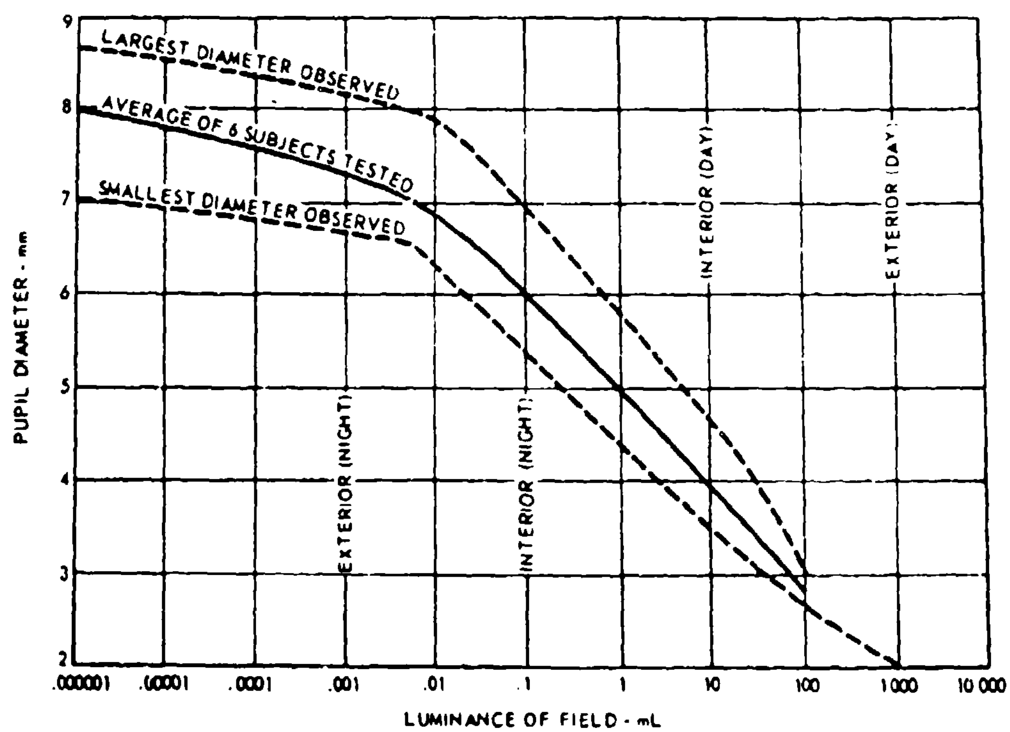

Figure 3.6 Pupil diameter as a function of uniform visual field luminance (from Roth and Finkelstein, ref. 19).

Pupil diameter does respond to other factors, including fatigue, stress, state of arousal, etc. It has sometimes been casually observed by the author that the pupil tends to constrict during eye tracker calibration procedures when subjects must concentrate on fixating certain target points and tends to dilate when a subject actually begins to fly an aircraft simulator and is apparently stimulated by the "exciting" nature of the task.

4.0 EYE TRACKER PERFORMANCE MEASURES

4.1 General Concepts

Terms specifying performance are sometimes used differently by different people and in different fields. The following discussions define these terms for the purpose of eye tracker specification.

4.1.1 Accuracy and Precision

As a general concept, accuracy is the difference between true line-of-gaze and measured line-of-gaze, usually expressed in terms of visual angle. It is a measure of how good the absolute eye position measure is, and there are many different specific ways in which this concept may be defined. Precision can be thought of as the amount of instrument noise (jitter) in the eye position measure when the observer attempts to keep the eye perfectly stationary.

As discussed in section 3, a real eye is never perfectly stationary and when people fixate a spot, they do not center it on the fovea with zero error. If a real eye is used to measure eye tracker accuracy and precision, this physiological uncertainty must be taken into account.

It is also important to be wary of tests using model (artificial) eyes. It is extraordinarily difficult to duplicate all the properties of a real eye and performance achieved with a model eye may be misleading.

Specific accuracy and precision definitions for the virtual cockpit application are proposed in section 4.2.

4.1.2 Linearity

Linearity is the extent to which a change in device output is proportional to change in eye position. Stated another way, it is the degree to which a plot of device output versus true eye position tends to be a straight line. The deviation from a straight line is generally specified as a percent of the size of the excursion.

Note that a device can have a large offset error and still be linear as long as changes in output retain proportionality to changes in eye position. When an application requires that a change or rate of change be determined, as opposed to absolute position, linearity is sometimes specified instead of accuracy. For the virtual cockpit application, accuracy is a more appropriate specification.

4.1.3 Resolution

Resolution specifies how finely the output scale is divided or, in other words, the smallest change that can ever be observed in the measured value. Resolution is introduced by digitization of a process and has no meaning for analog processes.

4.1.4 Update Rate and Transport Delay

Measurement update rate specifies the number of independent data samples per second provided by the instrument. The Nyquist criterion tells us that, in order to allow complete recovery of an input signal, data sampling frequency must be at least twice the highest significant input frequency component. This criterion assumes that an ideal filter, which is actually not realizable, operates on the sampled output. In most real situations, sample rate should be significantly more than twice the highest important frequency component.

Transport delay specifies the temporal relationship of each data sample to the actual event being measured. For example, a system might provide 1000 data samples per second, but the entire data stream might be delayed by 1 second. Thus, an event at t = 0 sec would appear in the data sample output at t = 1 sec and an event at t = 0.001 sec would appear in the data sample output at t = 1.001 second, etc. When an eye tracking device is referred to as a "60 Hz" system, for example, it usually means that the update rate is 60 samples per second and usually implies nothing about transport delay.

For applications that use the data to control or switch something in real time, the amount of transport delay is very important. On the other hand, if data is to be used only off-line (studies after the fact for research, etc.) transport lag does not matter at all, since it can simply be subtracted out.

Transport delay does not affect the frequency content or "wave form" of the information, it just determines when the information is received. Update rate does affect the information content. A slow update rate will cause high frequency information to be irretrievably lost. It can also interfere with the recovery of lower frequency information by "aliasing" from the higher frequency signals.

4.2 Specific Accuracy and Precision Definition

As previously noted, accuracy can be specified in many ways. The definition used should be compatible with real eye movement behavior and with practical means for testing. If testing is done with a real eye, we can be most confident of knowing true point-of-gaze when a person is asked to fixate a small stationary target for a short time. The most straightforward procedure for gathering such data is to have subjects fixate a set of predefined target points while eye tracker data are being recorded and then to compute the mean and standard deviation of the measurement during each fixation.

From figure 4.1 we can define fixation measurement error as the difference between true eye position and mean computed eye position during a fixation. An operational accuracy definition often used at Applied Science Laboratories is the expected (average) fixation measurement error. A more rigorous definition would specify a maximum fixation measurement error rather than the expected value. This can be expressed statistically as a 95% confidence interval.

Precision can be defined as a confidence interval about the mean during fixations. Again, assuming a normal distribution, precision can be expressed in terms of the standard deviation of the measurement (σ_M) during each fixation (see figure 4.1).

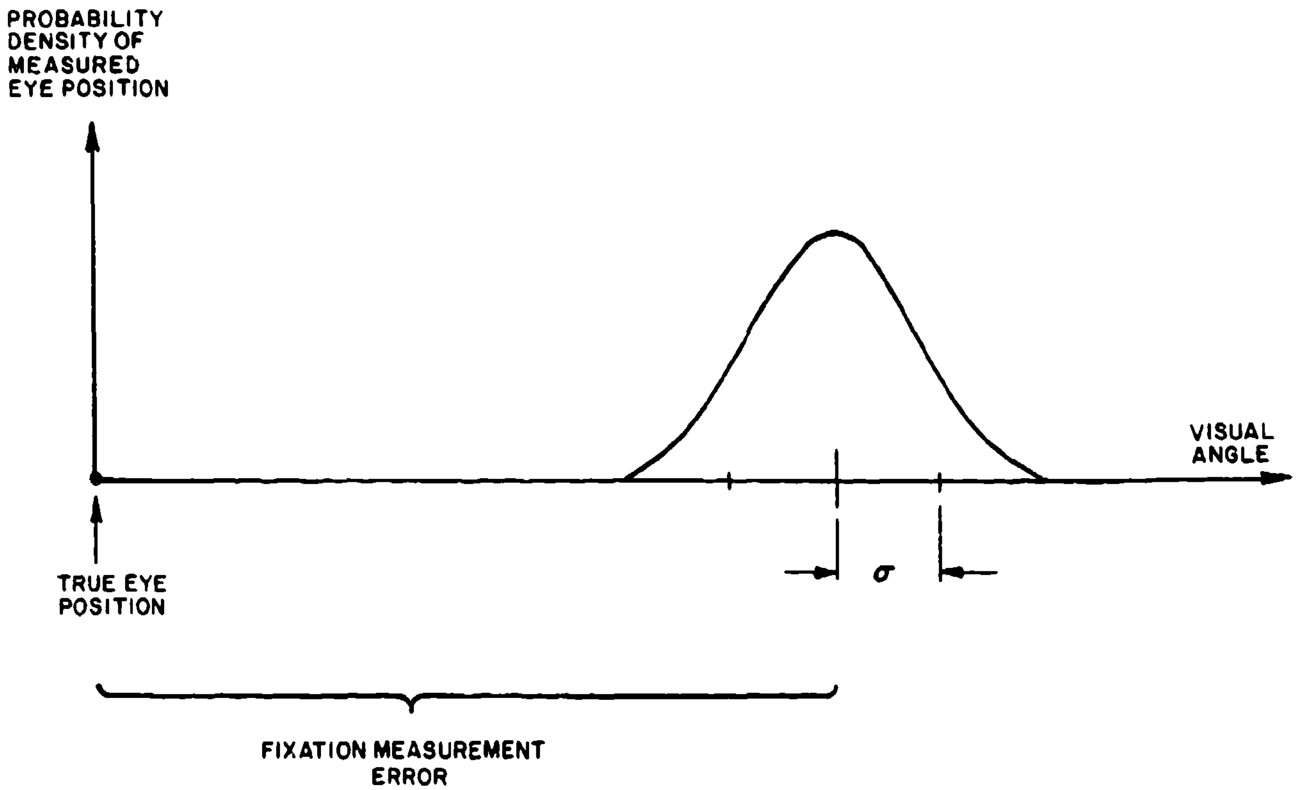

Figure 4.1 Fixation measurement error and standard deviation during a single fixation.

For the purpose of this report, we will use the following operational definitions:

- Fixation Measurement Error -- difference between true eye line-of-gaze and mean computed line-of-gaze during a fixation of some specified duration.

- Accuracy -- 95% confidence interval for fixation measurement error. Assuming a normal distribution, this can be estimated as $2\sigma_{FME}$, where σ_{FME} is the standard deviation of fixation measurement error.

- Precision -- 95% confidence interval about the mean measured value during each fixation. Assuming a normal distribution, this can be estimated by $2\sigma_M$ where σ_M is the standard deviation of the eye position measurement during fixations.

If tests are performed with real eyes, it must be understood that such tests will not strictly determine eye tracker performance, but rather the total accuracy and precision with which the eye tracker can measure a person's point-of-regard. The physiological variability discussed in section 3 will be included. Of course, total performance is ultimately the quantity of interest.

A value between 0.5 and 1.0 second is probably a reasonable choice for the fixation duration used to compute accuracy and precision (see fixation measurement error definition above). This range is consistent with maximum fixation durations that may occur during eye controlled switching and aiming tasks, but is not so long that it is difficult to maintain fixations.

If data are examined over an entire fixation, we can be confident of knowing point-of-regard (location of the target) to within the accuracy limit. The probability that a single measurement sample will be within a certain distance of true point-of-regard depends on both accuracy and precision. Assuming normal distributions and independence of the two components, the uncertainty associated with accuracy and precision can be combined by adding variances ($\sigma^2_{FME} + \sigma^2_M$). A 95% confidence interval (CI), or 95% circular probable error, for a single data sample can be computed as

$$CI = \sqrt{ACC^2 + PREC^2} \tag{1}$$

where ACC and PREC are accuracy and precision as defined above.

For the virtual cockpit application we will be dealing with a helmet-mounted eye tracker measuring eye position with respect to the helmet, a helmet mounted display, and a helmet position and orientation measurement device.

When considering line-of-gaze with respect to visual images that are defined with respect to the helmet, virtual images of switches for example, eye tracker accuracy and precision alone determine performance.

In cases where a pilot is looking at an external target, helmet position measurement errors must also be taken into account. For a single line-of-gaze measurement with respect to the cockpit, the 95% confidence interval (CI') is

$$CI' = \sqrt{ACC^2 + PREC^2 + CI^2_{hd}} \tag{2}$$

where CI_{hd} is a 95% confidence interval (or circular probable error) for the helmet orientation measurement.

In the special case of simulator applications for which all imagery is presented on the helmet mounted display, we never have to consider helmet orientation measurement errors in connection with eye tracking. The display system will always "know" where an image is with respect to the helmet. A helmet orientation measurement error might cause the image to be placed in the wrong spot on the helmet display and will affect the fidelity of simulation, nevertheless, point-of-regard errors need to be considered only with respect to the actual position of the displayed image.

4.3 Performance Enhancement Techniques

Because of the physiological variability discussed in section 3 and because of measurement limitations, it may not always be possible to make an open loop point-of-regard measurement with desired accuracy and precision. It may sometimes be possible to close the control loop and enhance performance, either by showing pilots their own point-of-gaze (section 4.3.1), or by giving the pilots a fine control adjustment that is independent of eye motion (section 4.3.2).

During smooth pursuit or compensatory eye movements, position errors in point-of-regard measurement will be introduced with lag or transport delay in the eye tracker or other parts of the visual display system. These errors can be reduced by careful lead compensation (section 4.3.3).

4.3.1 Secondary Visual Feedback

Secondary Visual Feedback (SVFB) refers to a display showing a person his own measured point-of-gaze. In the case of the virtual cockpit, this would consist of a cursor, circle, or highlighted area displayed by the Virtual Panoramic Display at the point calculated by the eye tracker to be the point-of-regard.

It was shown by Peli and Zeevi (ref. 20) that SVFB can improve smooth pursuit of targets moving at 1-10 deg/sec with respect to the visual field. It has also been shown by Kenyon et al. (ref. 21) that smooth eye movements can be generated by most people in the absence of a target, and that, when a target temporarily disappears, people are better able to maintain smooth pursuit tracking when SVFB is provided. These data imply a potential improvement in conscious fine control of eye movement with SVFB. The research indicates, however, that the above effects can degenerate when delay in the SVFB display is greater than 50 or 60 msec and when retinal error of the SVFB becomes larger than the fovea. Use of SVFB does seem to require concentration, and most experiments have included some practice time for subjects. There is a natural tendency to "chase" an SVFB display that is a little off-center with respect to the fovea. This effect may either lead to undesired eye movements away from the targets or an undesirable extra mental effort to suppress such movements.

SVFB may prove to be very beneficial in conjunction with the VPD/eye tracker by enabling pilots to correct for small eye tracking errors and

improve the effective system accuracy. On the other hand, the somewhat unnatural task of attempting to superimpose an SVFB cursor on a visual target may prove frustrating and annoying. Research will be needed to determine the efficacy of SVFB for performance enhancement of eye tracking in the virtual cockpit.

Even if SVFB proves not to be effective for enhancing performance, point-of-gaze feedback, in the form of a cursor, circle, or highlighted area, should still be available to enable the pilot to monitor eye tracker performance, when desired.

4.3.2 Head-Slaved Fine Positioning

Conscious fine control of eye position is not a task that comes naturally to people, even when secondary visual feedback is provided. Fine conscious control of head position is a far more natural task, as is alignment of two visual images.

If a cursor or aiming reticle that is normally slaved to eye motion (SVFB display) is frozen with respect to the helmet whenever the pilot activates a switch, then the pilot can visually fixate a target to quickly bring the reticle very close to the target, press the "freeze" button, and more precisely align the reticle and target with a small amount of head motion. Although this type of aiming would take longer than eye fixation alone, it would still be far quicker than moving a permanently head-fixed reticle all the way to an eccentric target (head slaved aiming) and may allow reduction of eye and head tracking errors. The small head motions involved would probably be possible even under high G's. It is not being claimed that the head can be pointed more precisely than the eyes, but rather that errors in measuring head and eye position might be more easily reduced with head controlled visual feedback than with eye controlled feedback.

The head slaving feature can be effective only when a visual target is relatively stable with respect to the visual field, since head tracking has been shown to be effective only at frequencies below about 0.8 Hz (ref. 22 & 23).

4.3.3 Lead Compensation

Delays or lags in the eye tracker and display system will result in position errors during eye movement. For example, if the eye is rotating at constant velocity, transport lag in obtaining and using an eye position measurement will produce a steady state point-of-regard measurement error equal to the delay multiplied by the target speed. We need to be concerned about such errors only during smooth pursuit or compensatory eye motions when the pilot will presumably be attempting to maintain point-of-regard on a visual target.

The delays in the system will be known and, therefore, the delay error can be reduced with a lead compensation scheme. The potential problem with lead compensation is that any high frequency noise (jitter) in the measurement will be magnified. To avoid this problem, the signal

should be low pass-filtered with a large enough time constant to reduce the velocity precision error to 2 or 3 deg/sec. A threshold should also be applied so that the lead term is used only when the smoothed velocity signal exceeds 2 or 3 deg/sec.

In the constant eye velocity example used above, there will be a lag in reducing the delay error that is approximately equal to the filter time constant and a similar overshoot when the eye motion stops. Since the velocity filtering introduces a lag term, this type of compensation makes sense only if the smooth pursuit and compensatory eye motions of interest have a frequency spectrum with a signficantly lower bandwidth than that of the lag term. As discussed in section 3, the smooth pursuit system usually exhibits a corner frequency on the order of 1.0 Hz, and, in the virtual cockpit applications, we will probably be dealing with even lower bandwidths. A velocity filter time constant of about 50 msec (3 Hz corner frequency) should be appropriate, and will probably be sufficient to suitably reduce velocity measurement noise.

To avoid producing overshoot errors after saccadic motions, the logic can be disabled whenever eye velocity is greater than 50 or 60 deg/sec.

5.0 VIRTUAL COCKPIT EYE TRACKING APPLICATIONS

The virtual panoramic display (VPD) is the visual portion of the virtual cockpit. The display optics will be helmet-mounted and the helmet will incorporate a magnetic position detection system and an eye tracker. The specific tasks requiring eye tracker data will be evaluation of candidate displays, cueing, eye-controlled switching, eye-slaved aiming, and pilot state monitoring. The following subsections discuss general eye-related tracker requirements for the virtual cockpit application, the specific eye tracker performance requirements for each task, and the resulting combined performance specification.

5.1 General Considerations

The virtual panoramic display (VPD) in the virtual cockpit will have a maximum binocular field of ±60 degrees horizontally by ±30 degrees vertically. The two VPD prototypes specifically considered in section 6 for eye tracker interface, the off-aperture and dual mirror systems, have horizontal fields of ±35 degrees and ±45 degrees respectively and vertical fields of ±18.75 degrees and ±22.5 degrees respectively (ref. 24). The horizontal range covered by the eye visual axis is about ±50 degrees, and only about ±40 degrees with comfort. The vertical eye movement range covers the entire vertical VPD display (see section 3.3). Ideally, eye tracker range should encompass at least ±40 degrees horizontally by ±30 degrees vertically. This ideal range will probably not be achievable, and will certainly not be achievable with maximum eye tracker performance. Maximum performance will probably be restricted to a 15 or 20 degree radius inner field (see volume 1, section 4.5.1).

The projected luminance of the VPD is 2000-3000 foot-Lamberts (1mL = .929ft-L). A uniform field luminance in this range would probably result in pilot pupil diameters of 2-3 millimeters. In general, however, the field will not be uniform and the projected luminance values may not always be achieved. In fact, a very brief test with three of the breadboard VPD helmets (described later in this report; section 6.2.1) resulted in significantly larger pupil diameters under most conditions. When used in real flight daylight conditions, the levels can easily equal or exceed 2000 foot-Lamberts, although this may be somewhat attenuated by the canopy and VPD combiner optics. Minimum scene luminance, at night or in a simulator when not much information is being displayed on the VPD, may be under 10 foot-Lamberts. Early on in an eye tracker development project, pupil diameter should be measured for a number of subjects under the expected range of realistic lighting conditions.

Different pilots will have slightly different eye locations with respect to a given helmet, even though the helmet may have a customized bladder or other custom fitting technique. When a pilot first dons the virtual panoramic display helmet, the eye tracker optics will have to be adjusted for that pilot's eye placement so that a properly centered and focused eye image is obtained. The adjustments will probably consist of turning 3 knobs on the helmet while viewing the eye camera image.

For simulator research applications, it is acceptable for these adjustments to be made by a technician, but, for later training and operational use, it should be possible for the pilot to do this. In either case, the adjustments should be straightforward and require no more than 1 minute. There should also be appropriate feedback to assure the simulator operator or pilot that proper performance is being achieved by the eye tracker. When the adjustments are made by the pilot, the eye image with recognition indicators can be displayed on the VPD during the process.

No matter how good the VPD helmet fitting system, there will be some motion of the helmet with respect to the head. Because the skin can move with respect to all parts of the face and head, slippage can be totally eliminated only with the use of a bite bar, which is obviously not acceptable. It is, however, important that the helmet fit as snuggly as possible without causing headache or other discomfort. Based on experience at ASL in other applications, it is reasonable to expect that slippage of the eye (the motion of an imaginary pointer located at the eye and rigidly connected to the helmet) will be restricted to about 4 mm. Kocian (ref. 24) reports that well-fitted flight helmets can be expected to slip no more than 3 mm. The eye tracker must therefore accommodate at least 3 to 4 mm of slippage to continue to perform acceptably.

In order to achieve maximum eye tracker accuracy, it will certainly be necessary for each pilot to go through a calibration procedure during which a number of displayed target points are fixated. It is important that it be possible for the pilot to self-administer this procedure, and that it take no longer than 1 minute. There must be feedback after the

calibration to assure the pilot or simulator operator that the calibration has worked properly. This feedback should, preferably, be in the form of a cursor displayed to the operator and/or the pilot, showing the pilot's point-of-gaze with respect to the scene. This type of feedback provides the clearest and quickest visual indication of how good performance is and the nature of any problems. Although such feedback need not necessarily be displayed all the time, it should be available at any time after calibration.

No matter how tight the performance specifications that are achieved, it is still prudent to allow for quick offset adjustments to be made at virtually any time, either by requiring the pilot to fixate a displayed target point and activate a switch, or by displaying measured point-of-gaze to the pilot and allowing continuous adjustments to be made with a four-way switch (left, right, up, and down).

A system to be used in flight, as opposed to just simulator use, must also have a small ruggedized electronics and processor package, preferably made with military specification components. Optical components must be mechanically capable of safely withstanding whatever vibration and g force will be encountered in the aircraft. The range of different scene luminance conditions encountered in flight will probably be far greater than for simulator use. To compensate for dramatic changes in ambient conditions, automatic adjustment of the eye tracker illuminator intensity might be required, in addition to automatic sensor gain control techniques.

5.2 Evaluate Candidate Display Formats

Display evaluation is a research application requiring off-line data analysis. The analysis will probably involve determining the amount of visual "traffic" between different display elements, the amount of dwell time spent on various elements in the display, the entropy (orderliness) of scan patterns, and, perhaps, the time required for visual reaction to certain displayed events.

All of these analysis tasks primarily require determination of fixation positions, start times, and durations. It will be important to differentiate among fixations on adjacent display elements. A 95% confidence interval for a single eye position measurement sample is given by equation (1) in section 4.2. If the adjacent edges of two potential fixation targets are separated by visual angle α, and we assume that point-of-regard is on one of these targets and not the space between them, then a single data sample from the eye tracker can be assigned to one or the other with 95% certainty if $\alpha/2$ is greater than or equal to CI from equation (1).

$$\alpha/2 \geq \sqrt{ACC^2 + PREC^2} \qquad (3)$$

In the case of off-line analysis, we can identify fixations and average them over the entire fixation, thus eliminating the "jitter" during fixations. Fixations are often defined as periods of at least 100 msec during which the eye does not move more than about 1 degree

visual angle. Reduction of the data to fixation points is generally part of the off-line analysis procedure anyway, and averaging over the entire fixation effectively eliminates precision as a consideration. All of the remaining error is encompassed in the accuracy definition, and we can just require that:

$$\alpha/2 \geq ACC \tag{4}$$

The details of display layout have not yet been determined, but it is anticipated that major symbols will be separated by about 1.5 degrees visual angle. This figure would imply an eye tracking accuracy requirement of about 0.75 degrees for the display evaluation task.

Fixations are never much shorter in duration than 100 msec and are usually longer than 200 msec. The minimum time required to initiate a saccade in response to a visual stimulus has been shown to be about 100 msec. There will probably be no need to look at the details of saccadic velocity for candidate display evaluation. A 60 Hz update rate is, therefore, quite sufficient for most off-line scan path analyses. In fact, much research of this type is done with 30 Hz samples. Transport delay can be subtracted out during off-line analysis and is not relevant.

5.3 Switching

Eye-controlled switch selection is a real-time eye tracker application that will enable the pilot to toggle a switch essentially by looking at it. The potential advantages over manual switching will be decreased time required to activate a switch, and improved ability to manipulate switches under high g conditions or when the hands are busy with other tasks. The protocol will probably require the pilot to note, via some sort of feedback, that the system has computed point-of-regard to be on the proper switch, and will then require the pilot to confirm the choice with a voice command or a manual consent switch. With the VPD, feedback could be some form of highlighting, a circle drawn around the switch, or some other visual indicator. Additional feedback in the form of a cursor showing computed point-of-gaze may or may not prove useful.

The feasibility of this sort of scheme was demonstrated by Calhoun, Janson, and Arbak (ref. 25). Subjects performing a tracking task were required to activate one of seven switches as soon as possible after receiving an audio cue. For a given set of trials, switch activation was accomplished either manually (by pressing the appropriate switch with the free hand), by eye-slaved switching with a manual consent switch, or by eye-slaved switching with a verbal consent response. When eye-slaved switching was used, visual feedback was provided by illuminating the chosen switch. The manual consent switch was a thumb activated push-button on the tracking task control stick.

After the appropriate learning period, average switching time, from the audio cue to final switch activation, was essentially the same for both manual switching and eye-controlled switching with manual consent

(1.7 - 1.8 seconds). Eye-controlled switching with voice consent took significantly longer, due primarily to delays in the voice recognition system used. This result suggests that eye-controlled switching may not provide a speed advantage over manual switching, at least not under the particular task loading conditions tested. A previous study by Calhoun, Arbak, and Boff (ref. 26) shows similar switching times (1.5 - 1.7 seconds) for a similar eye-controlled switching task with manual consent, and reported intermediate times measured from the audio cue, as shown in figure 5.1.

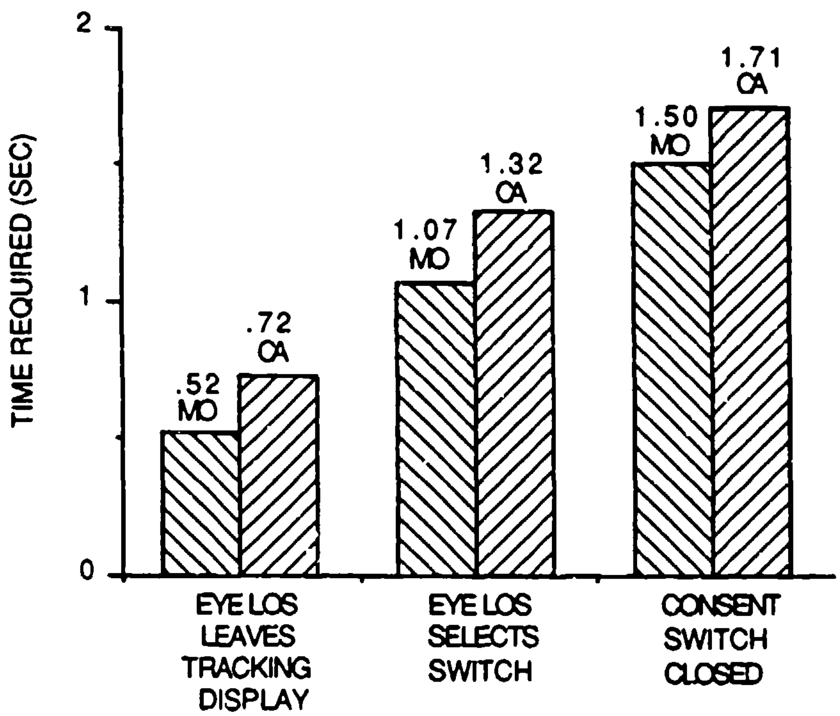

Figure 5.1 Eye-controlled switching response times for two subjects, from Calhoun et al. (ref 26).

Assuming the switches are visual targets with boundaries separated by a visual angle of at least α, then, as explained in the previous section, the most conservative performance requirement is

$$\alpha/2 \geq \sqrt{ACC^2 + PREC^2} \qquad (5)$$

The visual angle $\alpha/2$ can also be interpreted as the minimum envelope around the image of the switch within which eye position measurements will be considered to be "on the switch." In the Calhoun et al. experiment (ref. 25) this envelope was about 2 degrees from the center

of the switch.* If the system averages computed eye position over a running time window or passes the data through a low pass filter before comparison with switch positions, then the precision component can be reduced at the expense of increased lag. If we average over the same interval used to define accuracy and precision then, as explained in the previous section, we can effectively eliminate the precision error.

If eye position data samples were completely independent of one another (e.g., white noise) then, even if we averaged over a much shorter interval, the precision component could be divided by $\sqrt{n}$, where n is the number of samples being averaged.

The component of precision due to measurement noise will probably look "white" over the bandwidth of the eye tracker, but the physiological component, slow drift for example, will not. For illustrative purposes, we can make a conservative guess and assign 0.2 degrees as the precision component, (PREC') not due to relatively high frequency noise. If we can average only over a time interval signficantly shorter than the fixation duration chosen in section 4.2, our criterion then becomes

$$\alpha/2 \geq \sqrt{ACC^2 + (PREC^2 - PREC'^2)/n + PREC'^2} \qquad (6)$$

where n is the number of samples averaged. As mentioned in the previous section, α is likely to be about 1.5 degrees. Note that, by increasing the sample rate, we can increase n in equation (6) without increasing the time interval over which we average. The potential advantage is that α can be reduced, or accuracy and precision requirements relaxed.

It is reasonable to require the eye position measurement to be within the switch envelope for some minimum time before the switch is activated, otherwise the display system would have to respond whenever a saccade passed through a switch area. On the other hand, we ideally want no more than a barely-perceptible delay between the beginning of a fixation on the switch and feedback to the pilot, such as highlighting of the switch. Too long a delay will defeat the time saving purpose of eye controlled switching and will be frustrating to the pilot.

Assuming that the target envelope will not subtend more than about 2 degrees, a requirement of 20 msec within the target envelope would be sufficient to avoid confusion with saccades. The period must, however, include at least two or three data samples to make sense because a single sample contains no rate information. Depending on the eye tracker update rate, this may require more than 20 msec. Calhoun et al. (ref. 25) required that 2 out of 3 successive samples from a 60 Hz eye tracker be within about 2 degrees visual angle from the center of the switch.

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* If samples are independent and normally distributed with standard deviation σ, then the average of n samples is also a normal distribution with standard deviation $\sigma/\sqrt{n}$.

To be completely imperceptible, the delay between fixation and feedback would have to be less than 50 msec, but any delay of 120 msec or less should be minimally annoying. The total delay between fixation of a switch and feedback from the display is the sum of several components: the minimum time eye position is required to be within the switch envelope before switch activation, the eye tracker transport delay, any lag caused by time averaging, time required for the processor to compare the eye position data with switch positions, and time required for the display system to generate the appropriate highlight or cursor. The last two items will probably require no more than 2 display update intervals. Since the display update requirement is 60 Hz (ref. 24), this delay translates to about 33 msec.

An eye tracker update rate of 120 Hz with a 25 msec transport delay, a requirement of 3 consecutive fields within the target envelope, and a 3 field averaging window would add 75 msec of delay and produce a total feedback delay of just over 100 msec. A 60 Hz (50 msec transport delay) eye tracker with the same 3 field "on target" requirement and averaging window would result in a feedback delay of about 180 msec.

Once a switch is "activated" and feedback is received by the pilot, another 300 - 500 msec will probably be required for confirmation. Data reported by Calhoun et al. (ref. 26) indicate that on the average, about 400 msec was required for use of a joystick mounted consent switch.

Total time from fixation of the switch by the pilot to pilot confirmation of the selection should range from 400 - 700 msec for a 120 Hz eye tracker. Dropping the update to 60 Hz would add only about 80 msec to the process. Increasing the update rate beyond 120 Hz would not improve response time by more than about 50 msec. Considering these factors, the eye controlled switch task does not require higher than 120 Hz eye tracker update, and would probably be sufficiently effective with a 60 Hz system.

Time required to look to the switch from some other visual task depends on task loading and geometrical considerations that cannot easily be estimated. The same is true of time required to reach for a manual switch. For comparisons of different switching techniques it is, of course, the total switching time, as measured by Calhoun et al. (ref. 25), that is important. In terms of eye tracker specifications, the important point is that eye-controlled switching times cannot be reduced significantly by using extremely high update rate eye trackers.

The placement of virtual image switches within the display will be an important parameter for eye-controlled switching performance. Eye tracker range will probably be slightly less than the size of the display. Maximum eye tracker accuracy will probably be within about 20 degrees of visual field center and, therefore, best eye controlled switching performance will be obtained if switches are in this region.

Assuming that switch images will be stabilized with respect to cockpit coordinates, pilots will have to move their heads enough to place the switch images in the central region of the display for best

performance. Alternately, switch separation and the corresponding target envelope can be increased or head position fine tuning (see section 4.3.2) can be used when switches are in eccentric positions with respect to the head.

The closer the switches are to the display center, the shorter the distance, on average, that the eye will have to travel to fixate a given switch. Of course, it will also be important for other display features to be near the display center, and these considerations will have to be balanced when designing the layout.

5.4 Cueing

Eye line-of-gaze measurements can be used to facilitate communication of target positions or other spatial position information between pilot and copilot (backseater), two pilots, or a pilot and the ground. For example, assuming that both the pilot and copilot are equipped with a helmet mounted virtual panoramic display and eye tracker, the display system could, when appropriate, display the copilot's point-of-gaze to the pilot and vice versa. Such a display should probably be in the form of a highlighted area or outline subtending at least 3 or 4 degrees visual angle so that it will be easily noticeable with peripheral vision.

The system could also display to the pilot an arrow pointing the direction and providing a distance cue to the copilot's point-of-regard (or vice versa). This type of communication may prove to be far more efficient than verbal descriptions. Verbal communication would still presumably be required for one person to indicate to the other that there is something demanding visual attention.

It should be necessary to indicate target position only to within a parafoveal distance of 2 or 3 degrees. For a target that is stationary with respect to the visual field, this implies a very mild combined eye/head tracker confidence interval.

$$3 \text{ deg} \geq \sqrt{ACC^2 + PREC^2 + CI^2_{hd}} \qquad (7)$$

where CI_{hd} is a 95% confidence interval for the head tracker, as discussed in section 4.2.

If a moving target is being tracked, there will be additional uncertainty due to the characteristics of visual smooth pursuit (see section 3.2), but we cannot specify smooth pursuit error dependably enough to include this in the eye tracker specifications. We must simply realize that, for physiological reasons, point-of-regard cueing may be somewhat less dependable when the target is moving rapidly across the visual field.

Transport delay or lag in the eye tracker and display system will cause position errors during smooth pursuit or compensatory eye motions. Eye-slaved cueing probably makes sense for target velocities up to about 25 deg/sec. Delay errors will, therefore, reach maximum values of 25 deg/sec, multiplied by the delay. Assuming a maximum eye tracker delay

of three eye tracker update periods, 60 Hz, 120 Hz, and 240 Hz eye trackers would contribute maximum errors of 1.25 deg, 0.625 deg, and 0.3 deg respectively. If we again assume a 33 msec delay in the display system, then, for a 60 Hz eye tracker, we would have to reduce the 3 degree value in equation (6) to about 1.5 degrees. As discussed in section 4.3.3, the delay error can also be reduced by appropriate lead compensation.

5.5 Eye-Controlled Aiming and Target Designation

Ballistic weapons tend to have a projectile spread of about 5 feet per thousand, i.e., a little over 0.25 degree. Most effective use, therefore, requires aiming accuracy of about 0.125 degree. Super cockpit requirements listed in ref. 1 include eye aiming accuracy of 2 milliradians (0.1 degree), which is consistent with ballistic aiming requirements. This accuracy is well within the capability of people to align two or more visual images, as in traditional aiming tasks. Unfortunately, as discussed in section 3, people do not reliably position their eye visual axis with the same accuracy. Even if an eye/head tracking system could determine the eye visual axis direction without error, in the case of a stationary target it would not be reasonable to expect a 95% confidence interval for the eye visual axis to be smaller than 0.3 degree visual angle from the target. This is especially true if we are considering a wide range of subjects in a combat or simulated combat environment. For a target that is moving at more than 10 deg/sec with respect to the visual field, the confidence interval is even larger.

There are at least two ways in which this type of eye aiming task could be accomplished. The first is magnification of the target and surrounding area to reduce the eye pointing accuracy requirement. Magnification is possible if the pilot is looking at a virtual image created with information from some other sensor, but not if the target is being viewed directly. The second method is to use head movement for fine adjustment, as described in section 4.3.2.

Target designation, on the other hand, implies directing other weapon sensor systems (e.g., radar, heat seekers, etc.) to within the weapon launch envelopes. A 95% confidence interval of 1 degree is probably sufficient for this type of target designation, and eye-controlled target designation is a feasible task. It offers the significant advantages of potentially faster target acquisition and the capability to function in high g environments, where even head motion can be difficult and inaccurate.

The exact protocol for eye-controlled target designation should be the subject of significant simulator research, but will probably be similar in some respects to that for switch selection. The pilot will attempt to fixate the target. Feedback on the helmet mounted display, in the form of a highlighted circle, cross hairs, etc., will indicate the target locked onto by the weapons system, and the pilot will confirm and actually launch the weapon with a consent switch or voice command.

For a stationary target (with respect to the visual field), based on the assumptions discussed above, the accuracy and precision requirement is

$$1 \text{ deg} \geq \sqrt{ACC^2 + PREC^2 + CI^2_{hd}} \tag{8}$$

A threshold filter can be used to avoid introducing excessive delay and still prevent precision errors (jitter) from being transmitted to the weapon sensor servo. The threshold value should be about the same as the precision. This will effectively make system resolution equal precision.

Delay in target acquisition feedback to the pilot will depend on the weapon sensor system dynamics, the delay in display generation, the eye tracker delay, and any minimum fixation period required to lock on the target sensing system. Once the appropriate feedback is received, there will probably be a 200 to 600 msec delay for pilot confirmation. Even if the eye tracker delay is 50 msec, the maximum transport delay that would probably be associated with a 60 Hz update rate eye tracker, this will not be a very significant component of the total response time.

A weapon could potentially be fired at a target moving up to 25 deg/sec across the visual field. In the case of a target moving at this speed, delay or lag in the eye tracker and other parts of the weapon aiming system would produce a maximum aiming error equal to 25 deg/sec times the total delay in seconds.

Eye trackers with 3 update interval delays and update rates of 60 Hz, 120 Hz, and 240 Hz, would contribute maximum errors of 1.25 degrees, 0.625 degrees, and 0.3 degrees respectively. The other processing delays in the system will probably contribute at least as much error as the 60 Hz (50 msec delay) eye tracker.

It will certainly be advantageous to minimize the eye tracker delay component, but lead compensation will be necessary anyway if the system is to be successful against targets moving up to 25 deg/sec, and a 60 Hz eye tracker would probably be sufficient.

5.6 Pilot State Monitoring

Eye position information can potentially aid in determination of pilot intent, appropriateness of pilot actions, and the pilot's physiological state. Eye tracking measurements can aid in the first two categories by telling the pilot state monitoring system where the pilot has been looking. Visual behavior can then be evaluated by the system in terms of the current situation.

This type of evaluation can potentially be performed in near real time, but only with a time constant that is long compared to average fixation durations, since sensible evaluation of pilot visual scanning behavior can be made only by evaluating a series of fixations. For determining pilot intent or appropriateness of pilot behavior, eye

tracker performance requirements are essentially the same as those for display evaluation (section 5.2).

Eye movements provide several potential clues to physical and mental state although, in many cases, the relationships are not yet well understood.

The most obvious physiological clue involves not eye movement, but rather eye recognition by the eye tracker. If the eye tracker does not detect the eye for a period significantly longer than the time required for a blink (typically 200 msec), then there is either an eye tracker malfunction or the pilot's eyes are closed, perhaps due to unconsciousness or sleep.

Pupil diameter, usually computed by an eye tracker as a by-product of eye position determination, is clearly affected by alertness, fatigue, stress, and work load, among other things. These effects can best be demonstrated using very careful laboratory controls for target luminance and other variables that affect pupil diameter. This often involves averaging over many trials and normalizing with control trials. For these reasons, it is not yet clear whether pupil diameter will be reliable enough to aid in pilot state monitoring. At the very least, however, pupil diameter variations should be the subject of further research in the virtual cockpit, and pupil diameter data should be available from the eye tracker subsystem.

Tole et al. (ref. 27) and Ephrath et al. (ref. 28) have shown that the entropy or disorderliness of pilot instrument scanning behavior, as measured by Markov chain analysis, increases dramatically after a certain work load or stress threshold is reached. The threshold value seems to increase as a function of pilot skill. This phenomenon would also require further research for meaningful use by the super cockpit system. Eye tracker performance requirements would, again, be similar to those for display evaluation.

There is some evidence that peak saccadic velocities and velocity profiles change when subjects become psychologically or physically fatigued. Velocities as a function of saccade amplitude may tend to decrease and the velocity profiles may become more skewed (ref. 29 & 30). Measurement of this phenomenon would have a significant effect on eye tracker specifications, since a 240 Hz update rate would probably be required to measure saccadic velocity. This is the only potential application so far discussed that very clearly requires an update rate significantly faster than 60 Hz.

5.7 Consideration of Binocular Eye Tracking

Eye tracking, in theory, can be performed on either one eye (monocular eye tracking) or on both eyes (binocular eye tracking). Binocular eye tracking will require more helmet mounted optical components and more processing capacity than will a monocular system and, therefore, should be used only if significant benefits result.

The VPD display will be binocular and will probably include partial overlap of the monocular fields. The candidate display systems considered by Kocian in reference 24 all have overlap sections of 30 or 40 degrees.

When a pilot fixates a display element outside of the overlap section of the display, that element will be seen by only one eye. The appropriate eye accommodation will occur to focus the element being fixated and the accommodative convergence reflex (ref. 31) will result in the amount of convergence normally associated with that amount of accommodation. In other words, the eye not receiving the image will, nonetheless, point in the appropriate direction. Monocular eye tracking should, therefore, permit accurate point-of-gaze measurements, even on nonoverlapped sections of the display visible only to the nontracked eye.

Binocular tracking can, however, be used to extend the total measurable field by biasing the measurable field in different directions for each eye. This possibility is explained more thoroughly in section 6.2 (optical path design). The two monocular measurement fields will overlap, even if differentially biased, and, in these areas, binocular measurements could be used to increase dependability by providing some redundancy.

Binocular eye tracking would permit a measurement of vergence and thereby an indication of apparent range (distance from the observer) of the fixation point. The effective resolution of the range measurement will depend on the uncertainty in the eye tracker measurement as well as the range value. Figure 5.2 shows the convergence angles (difference in right eye and left eye azimuth angles) that would be required to exactly fixate a target at different distances directly in front of a subject. Note that as the target distance gets larger, the corresponding convergence angle rapidly becomes very small. A very small error in vergence angle can, therefore, represent a very large error in target distance.

The candidate displays considered by Kocian (ref. 24) all use a collimated display, so that displayed imagery appears at optical infinity. A collimated display will allow a pilot to switch attention between the display imagery and an out-of-cockpit scene without eye refocusing. Vergence information from a binocular eye tracker could potentially be used to distinguish between fixation on some close object within the cockpit, and a helmet-mounted display element that appears at the same position in the instantaneous visual field, but which is focused at infinity. This should apply primarily to display symbology that moves with the head. Imagery that is stabilized with respect to the cockpit will probably be positioned so as not to appear superimposed on important displays within the cockpit. In the super cockpit, as envisioned by Furness (ref. 32), all displays will be virtual images and the pilot may actually have little reason to look at physical objects within the cockpit.

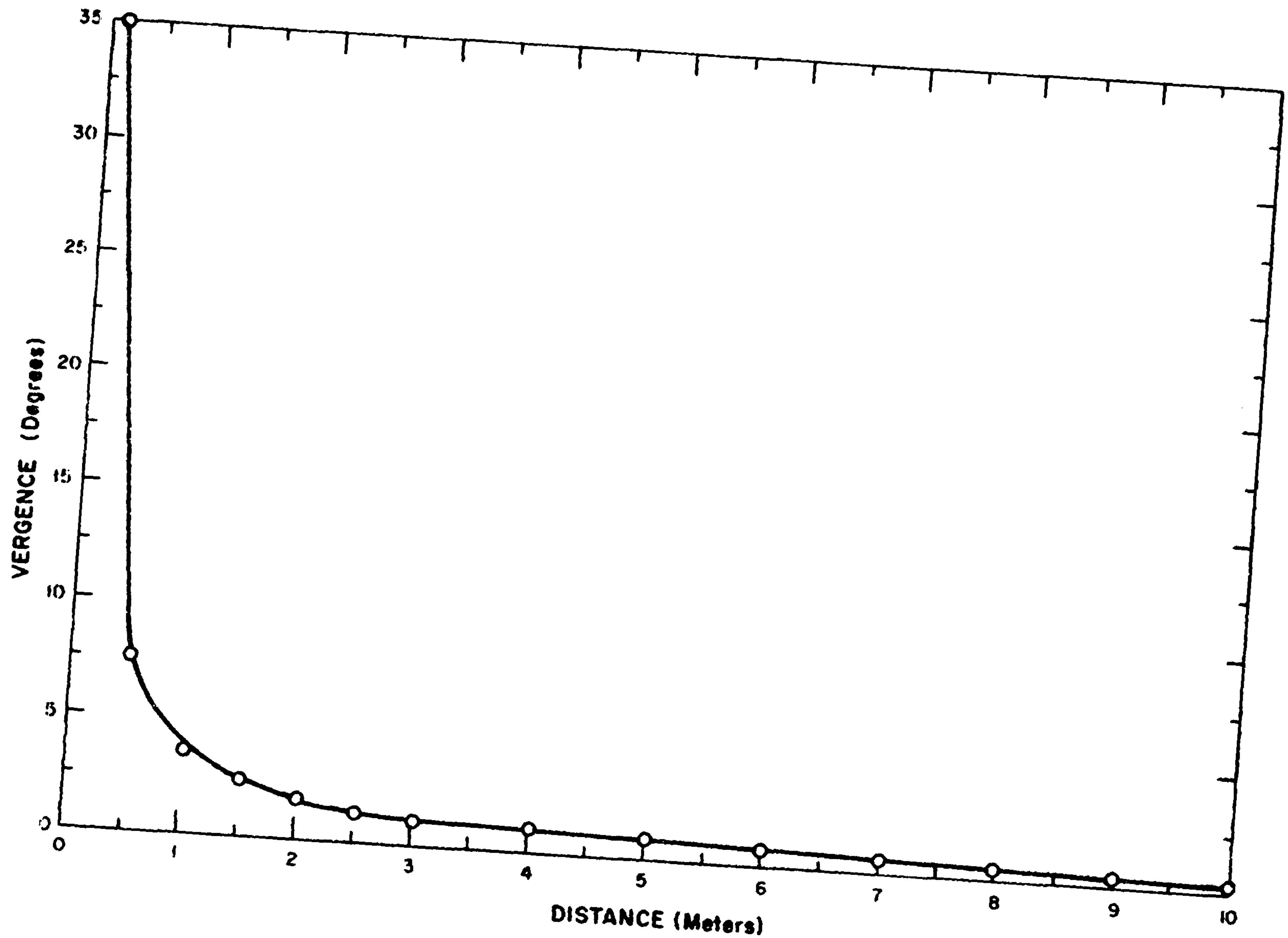

Figure 5.2 Eye vergence angle versus fixation point distance from the subject for target points directly in front of the head.

Stereopsis effects (perceptions of depth) can be produced in the display overlap sections by displaying the monocular images from different angles, in other words, by simulating binocular disparity. If stereopsis is exaggerated, correspondingly exaggerated eye vergence changes will result. There will also be a conflict between accommodation cues and binocular disparity cues, and it is not yet known whether such cue conflict will cause any problems.

If the VPD employs a large stereopsis effect, then vergence measurements from a binocular eye tracker could conceivably be used to distinguish between fixation of scene elements that are separated primarily by apparent depth. There currently is not, however, a good consensus on just how stereopsis will be used by the VPD, if used at all.

The potential advantages of binocular eye tracking are increased eye tracking range, some measurement redundancy, and the use of vergence data to measure apparent fixation point distances from the subject (at least for close distances). The drawbacks are increased complexity, an increase in the amount of helmet-mounted equipment, increased processing requirements and an associated increased cost. These drawbacks cannot be assessed quantitatively until eye tracker optical and processor designs for the VPD are more complete. Furthermore, potential advantages cannot be properly assessed until more is known about how the VPD will be used.

Binocular eye tracking is probably not essential for any of the applications discussed in sections 5.2 through 5.6 and it is, therefore, advised that the initial emphasis be on development of a suitable monocular system. The need for binocular eye tracking should be reassessed when both the VPD and monocular eye tracking designs are more complete.

5.8 Ideal Performance Specifications

The following set of helmet-mounted eye tracker performance specifications would be ideal to meet the virtual cockpit requirements discussed in sections 5.1 through 5.6. Accuracy and precision values correspond to the definitions in section 4.2. The resolution value was simply chosen to be less than precision. For the reasons discussed in section 5.7, a monocular eye tracker is assumed. In evaluating these

Range: $\pm$40 degrees Horizontal
$\pm$30 degrees Vertical

Accuracy: .7 degree

Precision: .35 degree

Resolution: .25 degree

Update Rate: 240 Hz

Transport Delay: 3 update intervals

Pupil diameter range: 2-8 mm

Optics Adjustment: Requires 1 min. or less after VPD helmet donned

Calibration Procedure:
- Requires 1 min. or less
- Can be self-administered by pilot
- Quick offset adjustment capability available after calibration

Tolerance for Helmet Slippage: 4 mm at the eye

specifications, it must be remembered that accuracy and precision correspond to relatively stringent 95% confidence intervals as opposed to the much looser "expected values", standard deviation values, or rms values often used.

It will probably not be possible to meet all of the above specifications, and some compromises will have to be made in task requirements. Most noteably, the vertical range probably cannot be extended all the way to -30 degrees for all subjects and 0.7 degree accuracy may not be possible over more than a 20 degree radius field. This will mean that, for best performance, pilots will have to move their heads enough to bring visual targets to the central 20 degree region of the visual field. In other cases, small compromises in task requirements may signficantly ease some performance specifications. For example, if we were to forego the possibility of saccadic velocity measurements for pilot state monitoring, a 60 Hz measurement update rate might be sufficient. The means for best achieving desired performance, and possible performance tradeoffs, are discussed in more detail in the following sections.

6.0 VPD EYE TRACKER DESIGN APPROACH

The following sections outline a design approach for a VPD eye tracker. The goal is to come as close as is reasonable to the ideal specifications derived in section 5.

The most important requirement for the virtual cockpit application is dependability and robustness. In a complex environment, like the one in question, the signal available to the eye tracker will often be less than ideal no matter what eye tracking method is used. It is essential that the system be "smart" enough to handle the "exception cases" that, in our experience, can make or break a system of this type. It is also essential that the system can be modified to handle unexpected problems that will inevitably arise when it is actually interfaced to the VPD.

It is proposed that the system employ the pupil-to-corneal reflex (CR) technique augmented with pupil tracking alone at eccentric eye positions beyond the CR detection range. Since the next generation VPD design has not yet been selected, eye tracker optical path design is

somewhat speculative, and is discussed with examples based on the "off aperture" and "dual mirror" candidate VPD designs described by Kocian (ref. 24). Similar principles apply to designs for other possible VPD systems. For the reasons explained in section 5.7, it is recommended that an initial eye tracker system be monocular, and it is proposed that a two-dimensional solid-state array device be used as the eye tracker sensor. Algorithm development and processor system design are discussed with an emphasis on performance robustness and compatibility with the virtual cockpit processor architecture.

As shown in the general block diagram of figure 6.1, the suggested system includes helmet-mounted optics, detector, and illuminator components; off-helmet camera electronics and processing system, peripherals for development and trouble shooting, and displays for feedback to researchers and simulator operators. Design choices and various subsystems are discussed in detail in subsequent sections. In one area we have proposed a staged development that will satisfy the more important performance requirements first, followed by less essential features. Specifically, we have suggested a 60 Hz prototype designed to easily accommodate subsequent enhancement to higher update rates.

6.1 Selection of Pupil-to-Corneal Reflex Technique

As described in Volume I (Review of Current Eye Movement Measurement Technology), current eye tracking techniques can be categorized as electro-oculographic, contact lens, and optical techniques. Optical techniques can, in turn, be divided into methods that detect single features on the eye, methods that detect differential motion of two features, eyelid tracking, and laser doppler velocimetry.

Potential techniques for integration with the VPD can be very quickly narrowed to dual feature optical techniques. The scleral coil contact lens method must be quickly eliminated as too invasive, and electro-oculography must be eliminated because of the associated dc drift problem (see sections 2 and 3 of volume I). Eyelid tracking is not nearly accurate enough, and it only works in the vertical axis. Laser velocimetry can be used to determine position only by integrating velocity and could, therefore, be used only in conjunction with a separate position measurement technique needed to correct integration errors and reset position after blinks. Single feature optical detection techniques all have relatively large errors when the detector moves with respect to the head. The helmet slip error associated with a limbus tracking technique, for example, is over 4 degrees for 1 mm of optics translation with respect to the head (see section 4.1 of volume I). All other single feature techniques will have even larger helmet slip errors and the VPD eye tracker must maintain better performance in the presence of up to 4 mm translation.

The dual feature techniques that have been used successfully are the pupil-to-corneal reflex technique and the dual Purkinje image technique. The dual Purkinje image method is by far the more precise of the two and, as implemented by SRI (ref. 33), can be used to measure the miniature

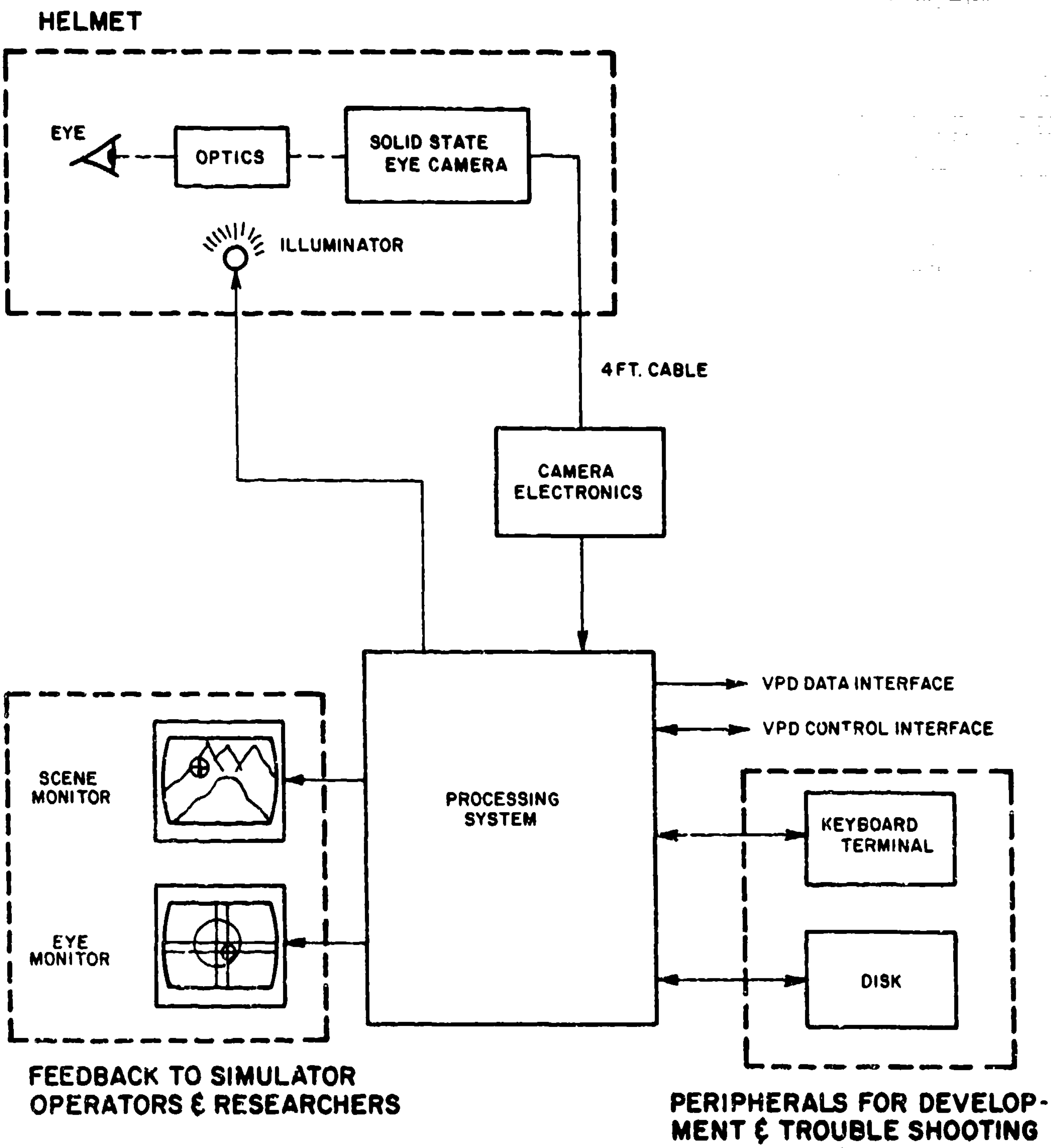

Figure 6.1 VPD eye tracker block diagram.

drifts and microsaccades that occur within fixations. The precision and accuracy requirements listed in section 5.7 could be more than satisfied by a similar device. The SRI device, however, has optics that are far too bulky to be helmet mounted, has a range of only about ±10 degrees visual angle, and requires large pupil diameters. With currently available technology, we cannot envision a successful dual Purkinje image system design that would be suitable for integration with the VPD.

The pupil-to-CR technique can be implemented with relatively small optics and lends itself to helmet integration. Current systems do not quite meet the accuracy and precision specifications listed in section 5.7, but come close enough that these specifications should be reachable. The range of the pupil-to-CR technique, which is limited primarily by the CR measurement, is at least as great as any optical technique except for pupil tracking alone.

Since a pupil center measurement is a by-product of the pupil-to-CR technique, the pupil alone can be used to extend the range, although with less than maximum accuracy. The update rate used by most current pupil-to-CR eye trackers is 60 Hz. A 240 Hz update rate is definitely possible, although it will require some extra development to create a small enough sensor package and it may make some other performance requirements more difficult to meet.

In short, the pupil-to-CR technique, possibly augmented by pupil only measurements at eccentric regions of the visual field, can potentially come the closest to the ideal requirements outlined in section 5. Therefore, we propose development of an eye tracker based on the pupil-to-CR method for integration with the VPD.

6.2 Optical Path Design

Generic bright and dark pupil optical designs are shown on figures 6.2 and 6.3. Note that the dark pupil illumination beam passes through one less beamsplitter and, other things being equal, would irradiate the eye with about twice as much light as the bright pupil illuminator beam. The size of the CR will be proportional to the angle, at the eye, subtended by the illuminator diffuser. The illuminator collector lens, field lens, and distance between them are determined by the size of the diffuser that is to be "filled" and the diffuser-to-eye distance.

At ASL, we have found that this type of illuminator design usually provides sufficient illumination while remaining well below eye safety limits, as defined by Sliney and Wolbarsht (ref. 34). Depending on the specific configuration, irradiation at the eye is usually between 0.1 and 0.5 mW/cm^2. If more power is needed, because the beam may have to pass through VPD optical elements or because of long optical path lengths, then the LED can be replaced with a more powerful incandescent source relayed to the helmet through a fiber optics cable. Alternately, the diffuser can be removed and the source optically magnified to subtend the necessary visual angle.

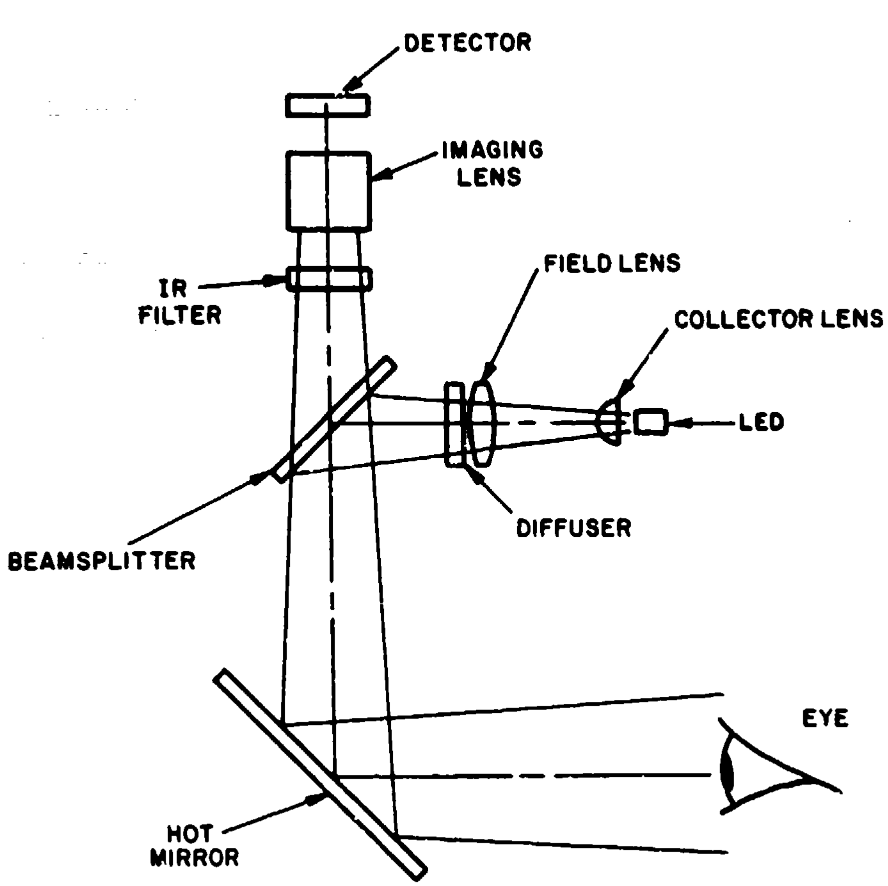

Figure 6.2 Basic bright pupil eye tracker optics.

The eye camera field-of-view should include the entire pupil during the worst case situation of maximum pupil diameter (8 mm), maximum eye rotation of interest (40 degrees horizontal), and maximum helmet slip (4 mm). These values require a horizontal camera field of about 27 mm at the eye.

A bright pupil optics system has a single central axis for both the detector camera and illumination optical paths. A dark pupil imaging system, on the other hand, must have separate illumination and detector paths. Even in the case of a dark pupil system, range will be maximized by keeping the two optical paths within several degrees of each other.

We will define the central axis as the eye visual axis when the pilot looks at the center of the VPD field. In the vertical plane, the illuminator and the detector optical axes should intersect the eye from below the central axis in order to minimize occlusion of the pupil by the upper eyelid. Experience at ASL indicates that vertical range with respect to the central axis will be maximized if the eye tracker optical axis is 10 to 15 degrees below the central axis. The resulting range is usually about ± 15 to ± 20 degrees with respect to the central axis for unoccluded CR recognition and about +30 degrees to -20 degrees for a reasonably unoccluded pupil.

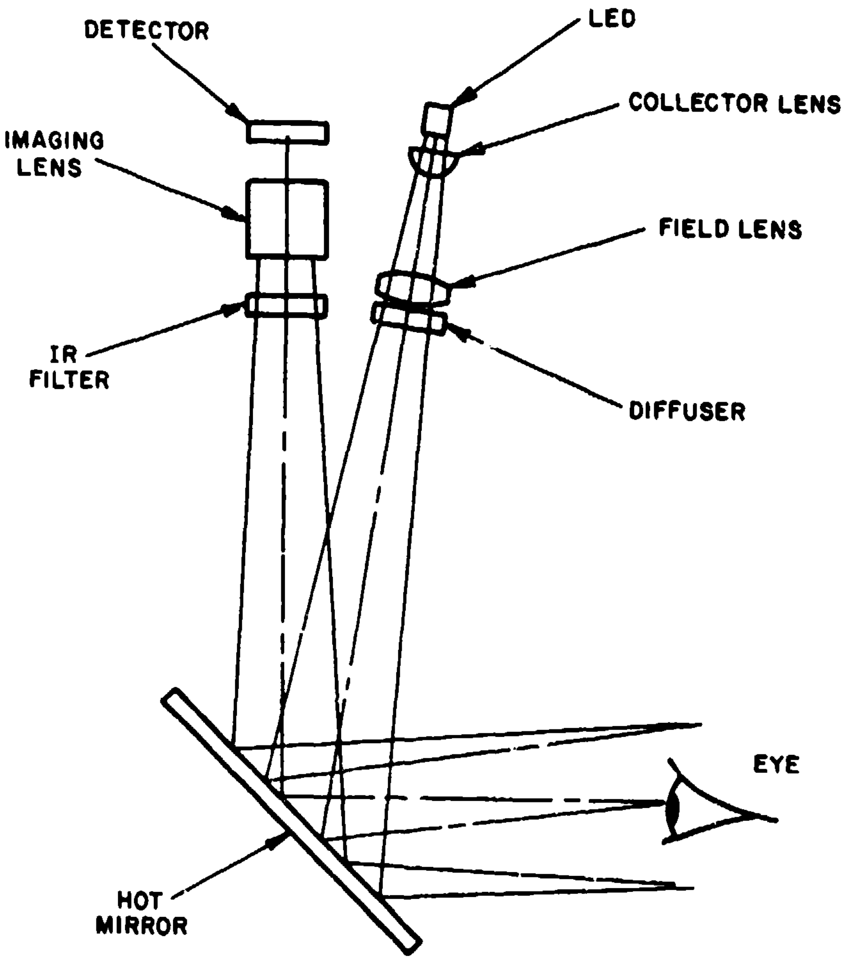

Figure 6.3 Basic dark pupil eye tracker optics.

In the horizontal plane, range about the central axis will be most symmetrical when the illumination and detector axes are biased to the temporal side of the central axis by about 6 degrees (the angle between the eye optical and visual axes). The resulting horizontal range for a measurable CR will usually be about ±20 to ±30 degrees.

If binocular eye tracking is used as discussed in section 5.7, it is possible to extend the total range by differentially biasing the two monocular fields. For example, assume that the detector axes on a binocular eye tracker were biased 11 degrees to the temporal side of the central line-of-gaze for each eye (instead of only 6 degrees as suggested above). The range for a measurable pupil and CR would be shifted 5 degrees to the left for left eye measurements, and 5 degrees to the right for right eye measurements. The total measurable field would be extended by 5 degrees on each side (to about ±25 to ±35 degrees), but a 10 degree band at each periphery of this extended field would be measurable with only one eye.

Certain optical path choices may require that the eye tracker look through one or more display components. Attenuation by such components must be considered. Furthermore, if both the illumination beam and detector path pass through the same optical surface, the specular reflection from that surface may form an image in the detector field-of-view, and may interfere with detection of the pupil and corneal reflex. Anti-reflective coatings, even multicoatings, usually do not completely eliminate such reflections. The location of the specular reflection image (a virtual image of the illuminator) is determined by the shape of the reflecting surface and the illuminator beam angle of incidence. This relation is illustrated in figure 6.4 for a spherical combiner surface.

The remainder of the optical path design is dependent on the VPD configuration. In the following subsection, a brief experiment is described using the off-aperture, dual mirror, and pancake window breadboard helmets. In the subsequent two subsections, optical path possiblities are presented, as examples, for the off aperture and dual mirror systems. The optical path discussions apply equally to bright or dark pupil eye tracker optics.

Similar analyses are possible for other display designs, including the pancake window system, a holographic system made by Hughes (ref. 24), a helmet-mounted display made by GEC incorporating night vision sensors (ref. 35), and others. A rigorous optical path design and prototype construction for a particular display will require detailed drawings of the display optics and/or a sample system that can be dismantled for experimentation.

6.2.1 Experiment with Breadboard VPD Designs

A very brief experiment was performed with off aperture, dual mirror, and pancake window breadboard systems at the AAMRL facility. Small dark and bright pupil optics modules were hand-held at various positions to obtain eye images while a subject wore one of the VPD breadboard helmets. The dark and bright pupil optics modules were similar to those shown in figures 6.2 and 6.3, except that the hot mirror shown in those figures was not used. The detector was a miniature video camera and the field-of-view at the eye was about 25 mm wide by 20 mm high. The resulting images were displayed on a monitor and were also recorded on a VHS video cassette recorder.

With each VPD optics systems, stroke, typical raster scene, and flat field (uniform brightness) raster displays were used to provide data under different scene luminance conditions, although luminosity was not actually measured. The flat field raster displays represent an upper bound to scene luminance for each display with the raster scene representing a more typical case and the stroke display representing a minimum brightness condition. All tests were performed indoors, mostly with room lights off, and the display, therefore, provided virtually all of the luminance in the subject's visual field. Only one subject was tested with each display. Whenever one of the eye imaging optics

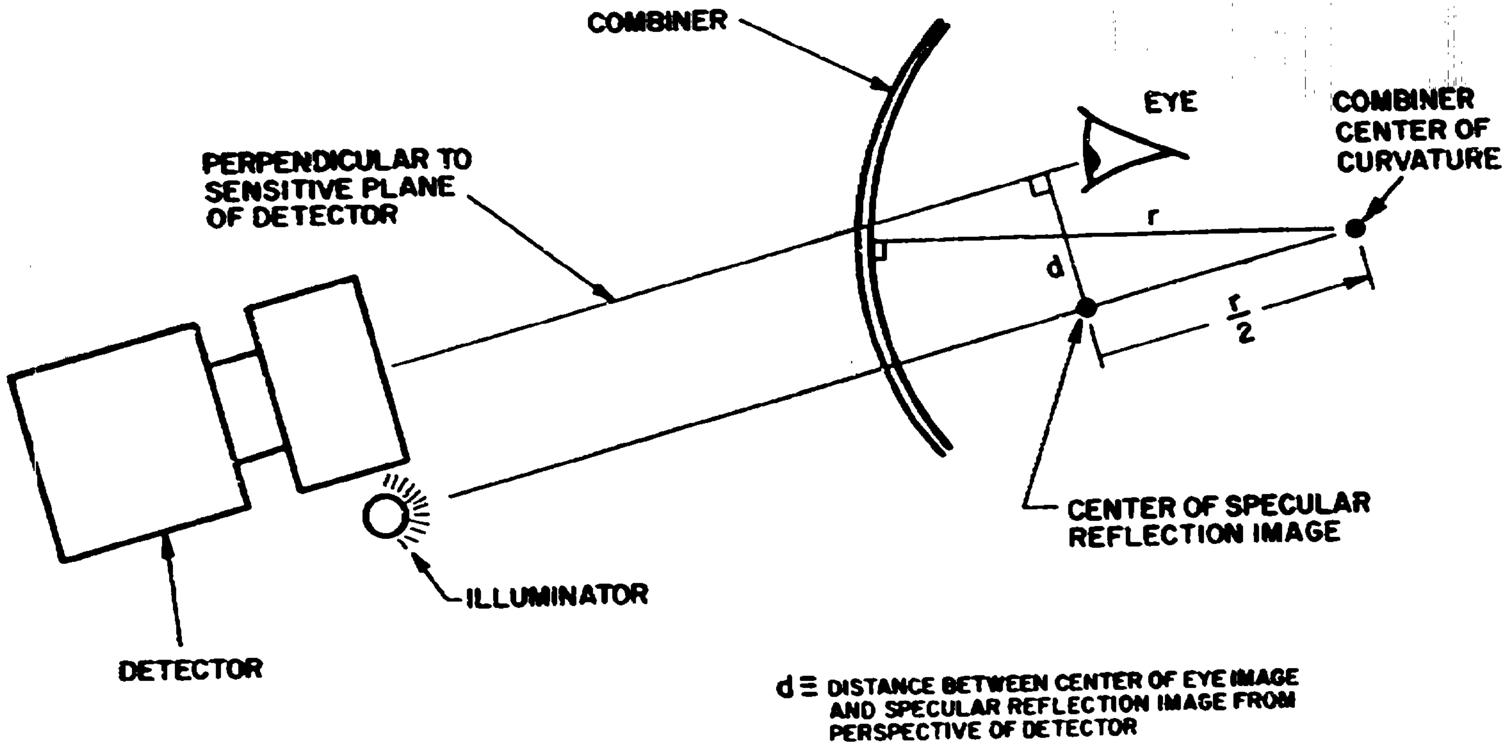

Figure 6.4 Location of specular reflection image from a spherical combiner in front of the eye.

modules was focused at a new distance, a ruler image was later recorded at the same distance to provide a reference for determination of pupil diameters.

Figure 6.5 is a sketch showing the off aperture design concept. Helmet mounted projectors direct an image to curved (mildly aspheric) combiners in front of each eye which act as both mirror and lens for the projected images. The pilot will see both the projected image and the real scene through the beam splitters. For the current breadboard design, the display field-of-view is 50 degrees horizontal by 37.5 degrees vertical (ref. 24). The eye relief (minimum distance from the eye to combiner) is about 56 mm.

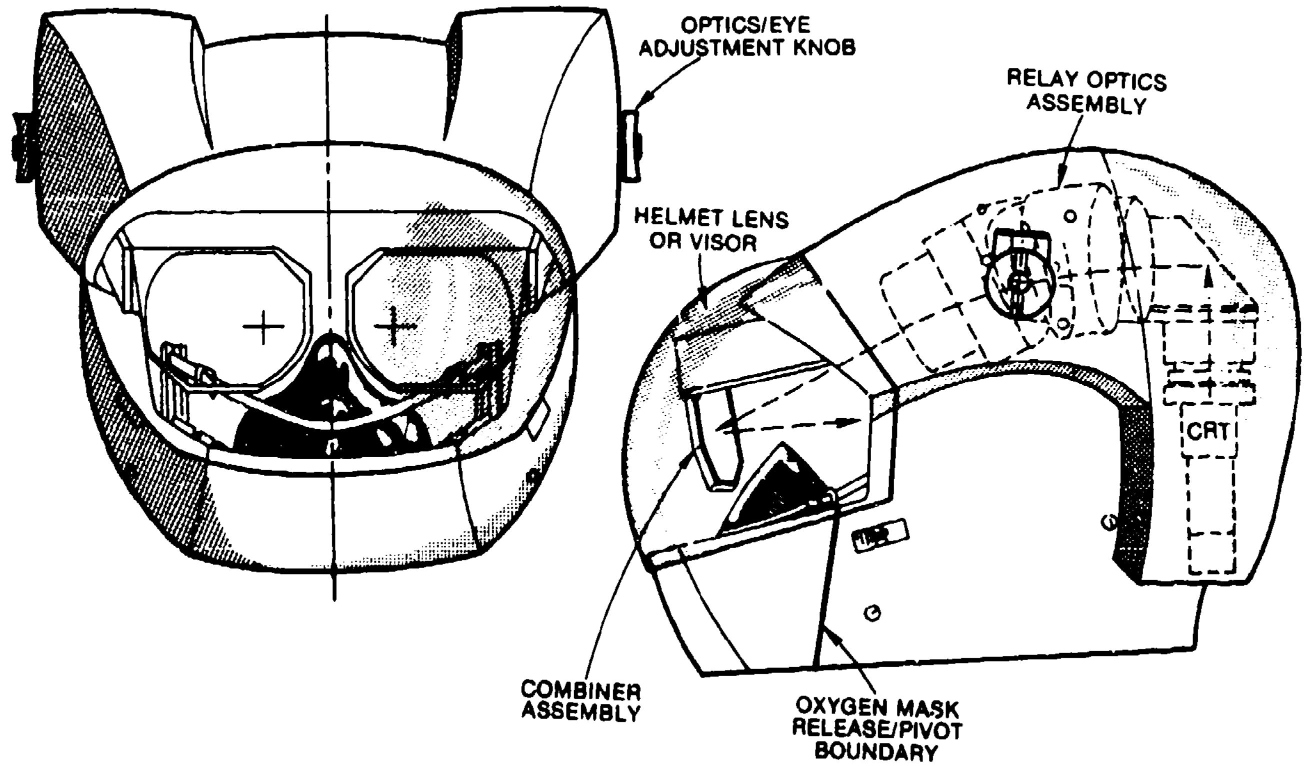

Figure 6.5 Off-aperture VPD helmet concept, from Kocian (ref. 24).

The dual mirror design is shown in figure 6.6. The display is projected from below to a combiner/beam splitter assembly. The display field-of-view is 50 degrees horizontal by 45 degrees vertical with an eye relief of about 32 mm (ref. 24).

The pancake window system (figure 6.7) reflects a projected polarized display image from a flat combiner through the puncake window. The pancake window, used to create a collimated virtual image of the display, consists of a curved combiner plus a series of flat combiners,

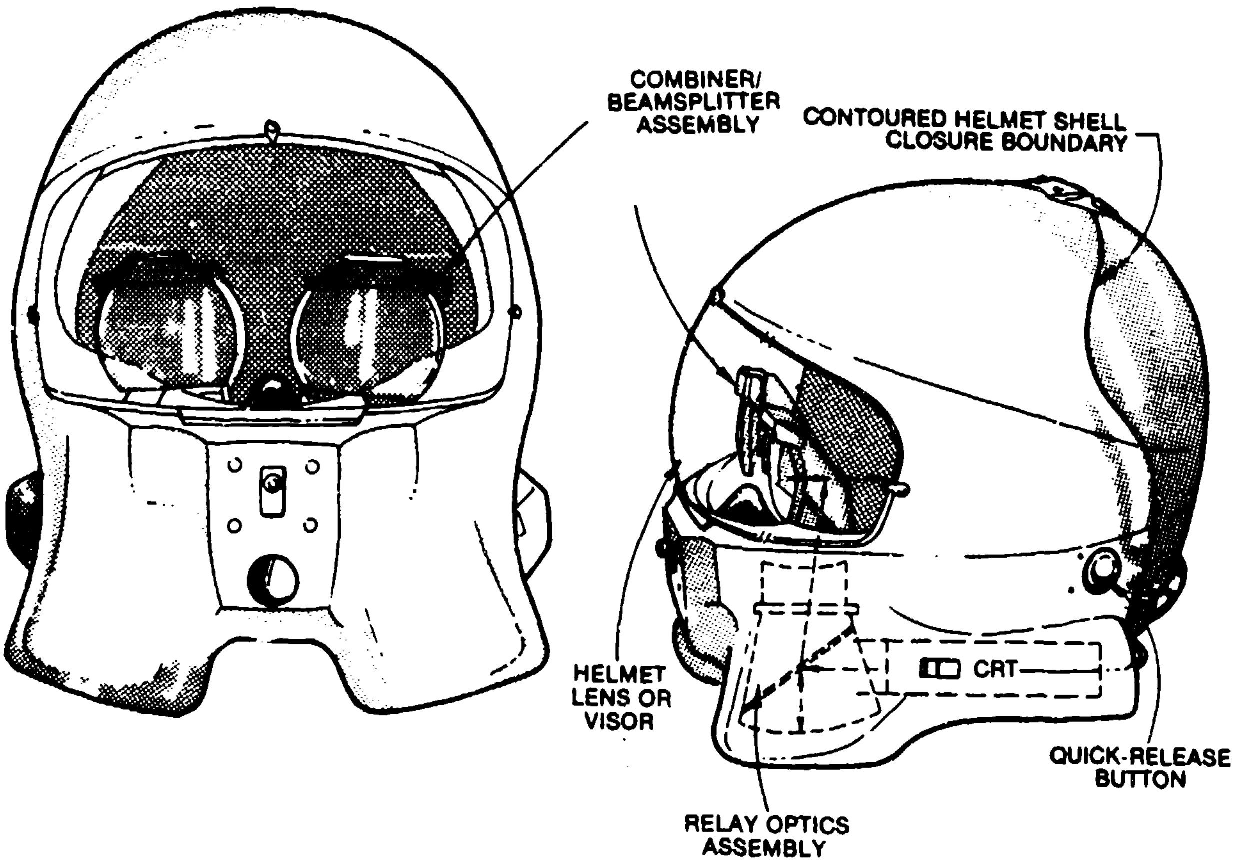

Figure 6.6 Dual mirror VPD design concept, from Kocian (ref. 24).

polarizers, and quarter wave plates. A detailed explanation of the technique can be found in reference 36.

Pupil and corneal reflection images easily detectable to an observer were obtained, with both bright and dark pupil optics, through the off aperture system curved combiner, and through the entire beam splitter/combiner assembly on the dual mirror system. In the case of the pancake window system, a detectable image could be obtained through the pancake window from the nasal side of the flat combiner; but not through both the flat combiner and the pancake window, primarily because of multiple specular reflections in the image.

In the case of the off aperture system, a suitable image was also obtained looking from just below, rather than through, the curved combiners. The geometry of the other two systems (dual mirror and pancake window) did not permit a clear view of the eye without looking through some of the display optics components, as previously described.

Specular reflections from display components created some difficulties with both the dual mirror and pancake window systems,

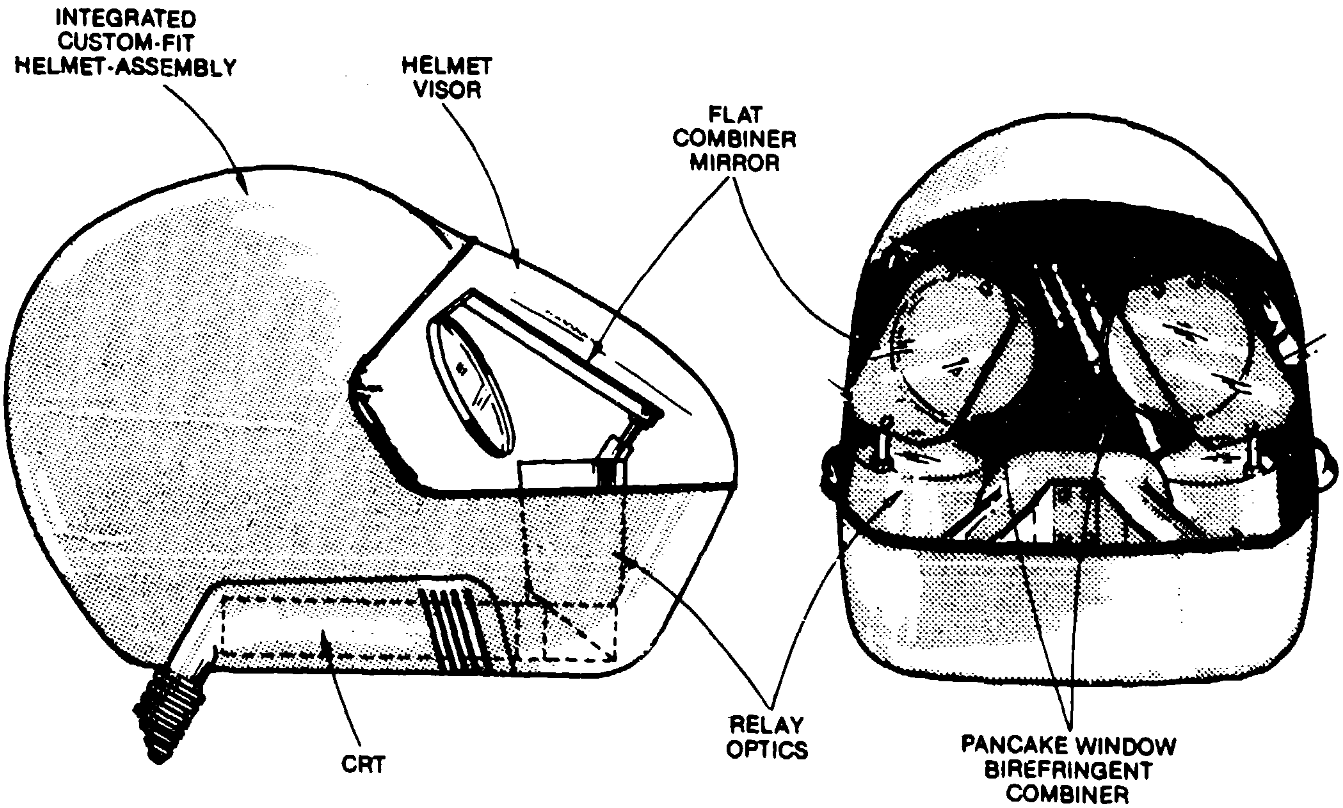

Figure 6.7 Pancake window design concept.

especially when using the bright pupil optics module. In the case of the dual mirror system, the specular reflection from the curved combiner tended to cover the pupil unless the optical path was well below the central line-of-gaze. Mechanical obstruction by the lower helmet cowling prevented the hand-held bright pupil optics module from being positioned as far below the central line-of-gaze as would probably be ideal; but when held so that its smallest dimension was oriented vertically, it was possible to position the optics module so that the specular reflection was just out of the camera field. With the pancake window system, the oxygen mask assembly caused a similar mechanical restriction. The best bright pupil image achieved had a large specular reflection (from the pancake window) several millimeters below the pupil, but still well within the video image field when the pupil was centered. Because the optics were hand-held and the helmet was not stabilized, actual optical path angles could not be determined.

The dark pupil images were less of a problem because the noncoaxial illuminator beam (see figure 6.3), which is displaced by about 5 degrees from the detector path, could be placed at larger angles with respect to central line-of-gaze more easily. For example, when the dark pupil

system camera had approximately the same optical path with respect to the pancake window helmet as the bright pupil camera, the dark pupil illuminator beam was 5 degrees lower than the bright pupil beam. The specular reflection from the pancake window was far enough below the dark pupil to remain out of the camera field-of-view.

Thorough assessment of potential specular reflection problems will require accurate drawings of the display components involved and their position relative to the eye. Alternately, the breadboard display optics must be partially disassembled so that an optical bench can be used for precise empirical experiments.

Using the off aperture display optics, pupil diameters varied from 5.6 to 6.0 mm with the stroke display, 4.8 to 6.0 mm with the raster scene display, and 2.6 to 3.0 mm with the flat field raster display. Using the dual mirror optics, pupil diameters were in the range of 4.5 to 5.5 mm with all displays (stroke, raster scene, and flat field raster). Using the pancake window optics, pupil diameter values were 5.0 to 5.5 mm with the raster scene display and 4.0 to 5.0 mm with the flat field raster display. The stroke display was not tested with the pancake window system. In all of the above cases, both dark and bright pupil images had an easily-discriminable pupil and corneal reflex. Aside from potential specular reflection problems, all images were probably suitable for automatic recognition by an eye tracker.

Pupil diameter can vary considerably between subjects and for the same subject at different times. Only one subject was used for each test and the test conditions were less than rigorous. Results from this brief experiment must, therefore, be regarded as only a preliminary indication of conditions that will be encountered.

We can conclude that, if necessary, infrared light transmission is probably sufficient for an eye tracker through the off aperture curved combiner, the dual mirror combiner assembly, and the pancake window. If an eye tracker optical path must pass through the dual mirror combiner assembly or through the pancake window, specular reflections may or may not present a problem. This potential problem can be further investigated, as previously described. The helmet-mounted displays alone do not appear to be bright enough to reduce pupil diameters significantly below 3 mm. The effect of a real daylight scene under actual flight conditions was not considered. It is not yet clear whether dark or bright pupil optics will produce the best image under the full range of expected conditions.

6.2.2 Possible Eye Tracker Optical Paths for Off Aperture VPD Design

The off aperture design was described in the previous section and is shown in figure 6.5. The basic potential paths for eye tracker optics are shown in figures 6.8 and 6.9. Paths 1 and 2 do not require the addition of optical surfaces within or near the pilot's field-of-view. These paths are the preferred choices for minimum obtrusiveness and minimum modification of the current planeform. There are, however,

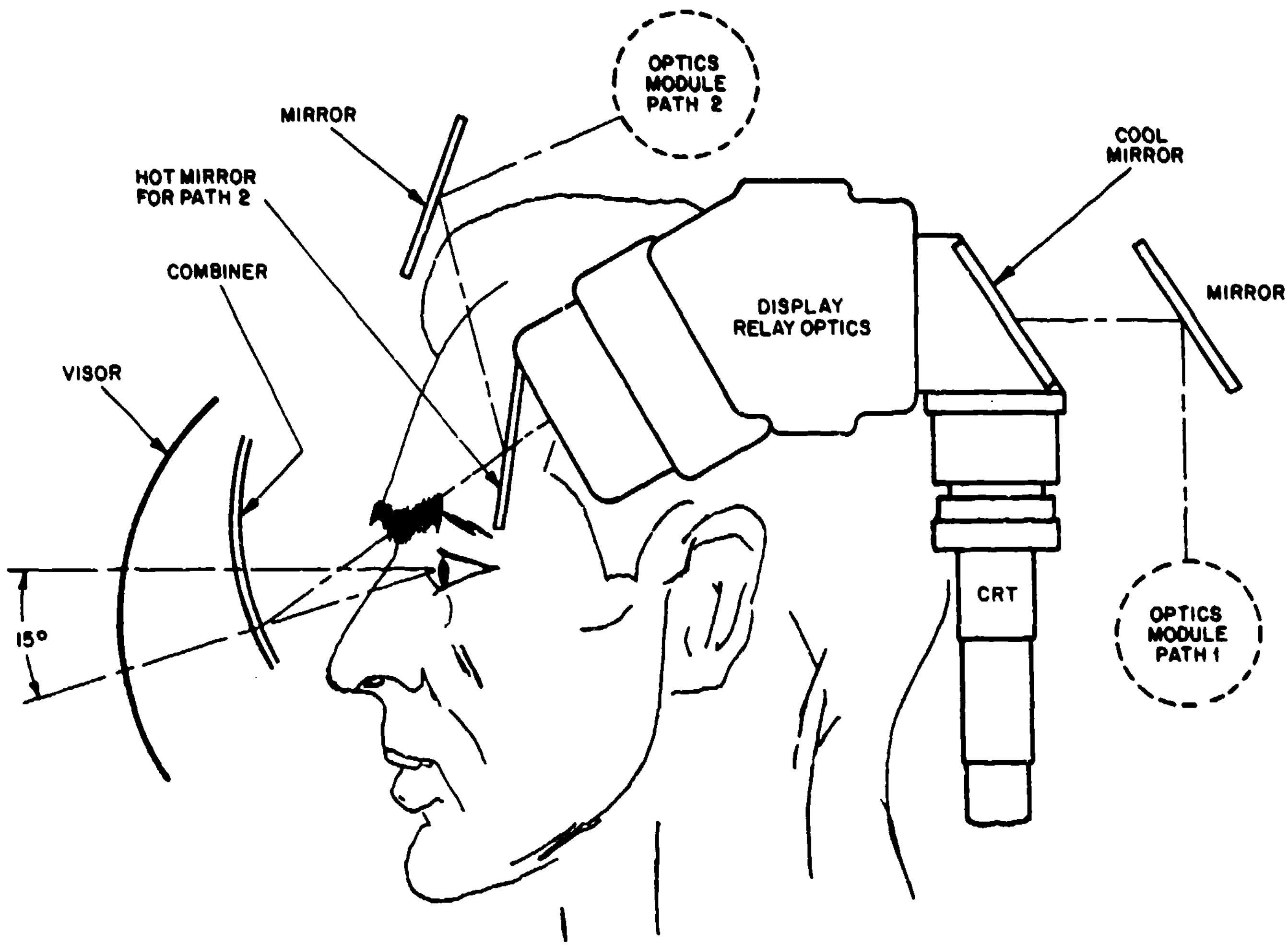

Figure 6.8 Eye tracker optical path choices for off aperture VPD helmet.

a potential optical problems that cannot be fully evaluated without more detailed knowledge of the display optics or additional experimentation with a prototype device.

Path number 1 passes through the display relay optics. The details of the relay optics are not available, but since the eye sees the CRT image focused at infinity, it follows that, with appropriate optics, the eye can be imaged from the position of the CRT. More information is needed, however, to determine the exact nature of such optics. The 45 degree mirror in the display path just above the CRT would have to be replaced with a "cool mirror," i.e., a mirror highly reflective in the visible spectrum for the display and highly transmissive in the infrared

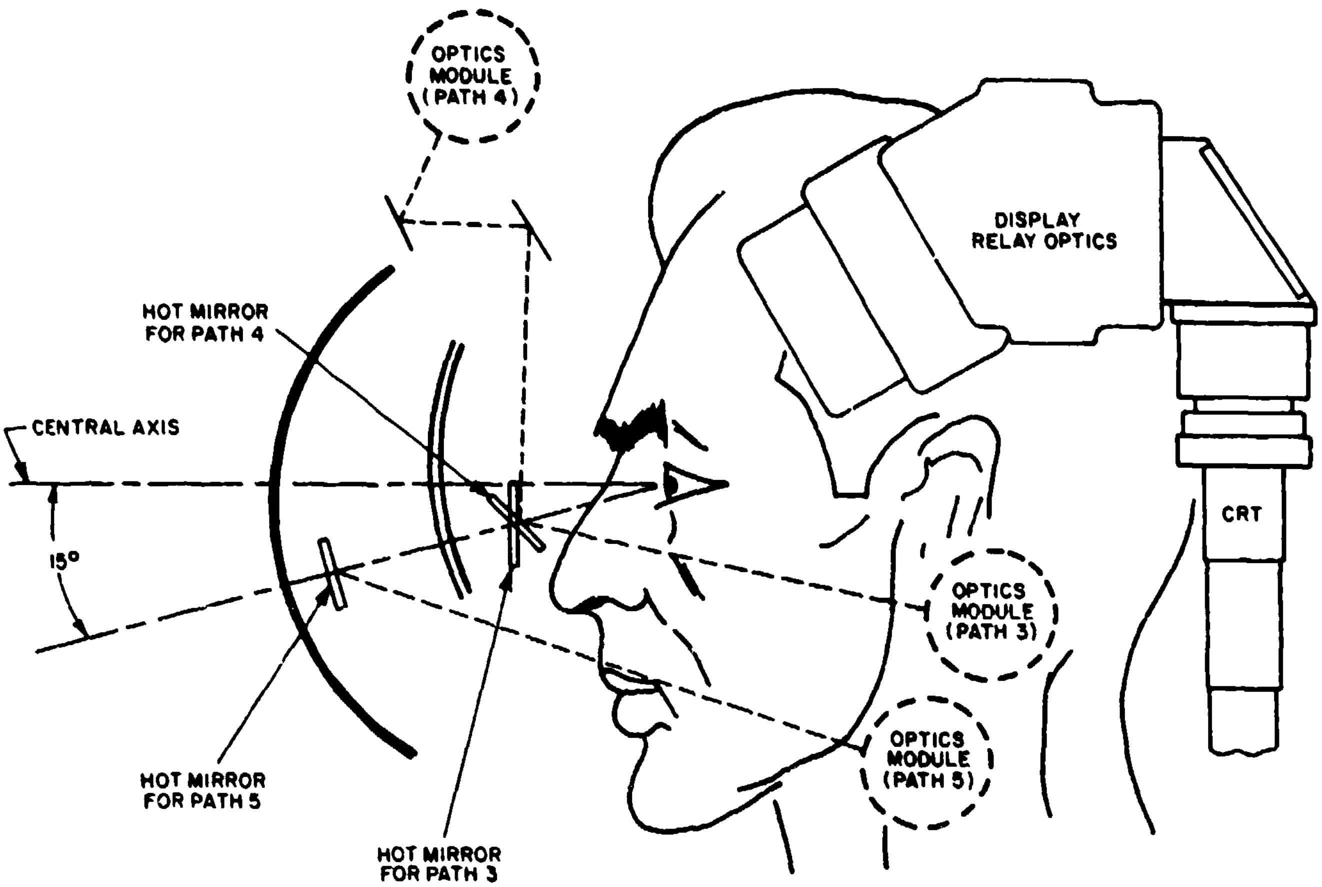

Figure 6.9 Additional eye tracker optical path choices for off aperture VPD helmet.

for the eye tracker. It is probably possible to achieve a coating that would be adequate for both the display and the eye tracker, but this must be experimentally verified. An infrared reflective coating would also have to be added to the curved display combiner. The most serious potential difficulty is that the eye tracker illumination beam would have to pass through multiple optical elements in the relay assembly and will form specular reflections on all of them. At least some of these reflections would probably be in a critical part of the detector field and, even with anti-reflective coatings on the elements, might interfere with eye tracker performance.

The path labeled number 2 would not have the specular reflection problem, but some other issues must be considered. The curved combiner will probably produce a magnified image of the eye near the front of the relay optics assembly. More detailed information about the combiner is needed to determine the exact properties of such an image and the optics

necessary to obtain an unaberrated eye image at the eye tracker detector. If detector optics need to be large, this would be contrary to the goal of minimizing helmet-mounted equipment. A hot mirror would be required at the end of the display relay optics to reflect the infrared eye tracker light while passing the visible display light. As in the case of path number 1, the curved combiner would need an infrared reflective coating.

Path number 3 in figure 6.9 is the closest to current ASL helmet mounted eye tracker optics, and is the most straightforward in terms of eye tracker performance. The eye tracker combiner (hot mirror) would, however, be in the path of the display beam. Although it would be coated for maximum transmittance and minimum reflectance in the visible spectrum, this beam splitter may, nonetheless, interfere with display performance. The eye tracker beam splitter would also decrease eye relief (distance from the eye to the nearest optical surface). By increasing the optical path angle from 15 to about 25 degrees below central line-of-gaze, the hot mirror could be moved below the display combiner and out of the display path. Increasing this angle will displace the measurable field-of-view downward, and may make the corneal reflex undetectable when the subject looks at the top of the display.

Path number 4 is similar to 3, but requires an extra mirror to bend the path around the crown of the helmet so that the camera and illuminator can lie flush against the crown of the helmet. The path length is also a bit longer.

Path number 5 would not interfere with the display in any way. The primary disadvantage to path number 5 is that it requires that a hot mirror be supported at a long distance from the helmet center of mass. This hot mirror would probably have to be supported by the lower helmet cowling. The path also must pass through the curved display combiner but, as indicated by the test described in section 6.2.1, this should not be a problem.

6.2.3 Possible Eye Tracker Optical Paths for Dual Mirror VPD Design

The dual mirror design was described in section 6.2.1 and is shown in figure 6.6. Figure 6.10 shows the optical path that would present the fewest optical problems for implementation of an eye tracker. The infrared transmittance of the beam splitter/combiner assembly was shown to be sufficient by the test described in 6.2.1. Determination of the specular reflection location will require knowledge of the spherical combiner radius of curvature and the precise location of its center of curvature with respect to the eye (see figure 6.4).

A second path, not shown in figure 6.10, is also a possibility. The flat element in the beam splitter/combiner assembly could be coated for infrared reflectivity and used to reflect an eye image upward. Because of the position and orientation of this flat combiner, the reflection of a ray that intersects its surface from below the central line-of-gaze would probably be directed toward the pilot's eyebrows or just above. A relay mirror would, therefore, be required a very short distance above

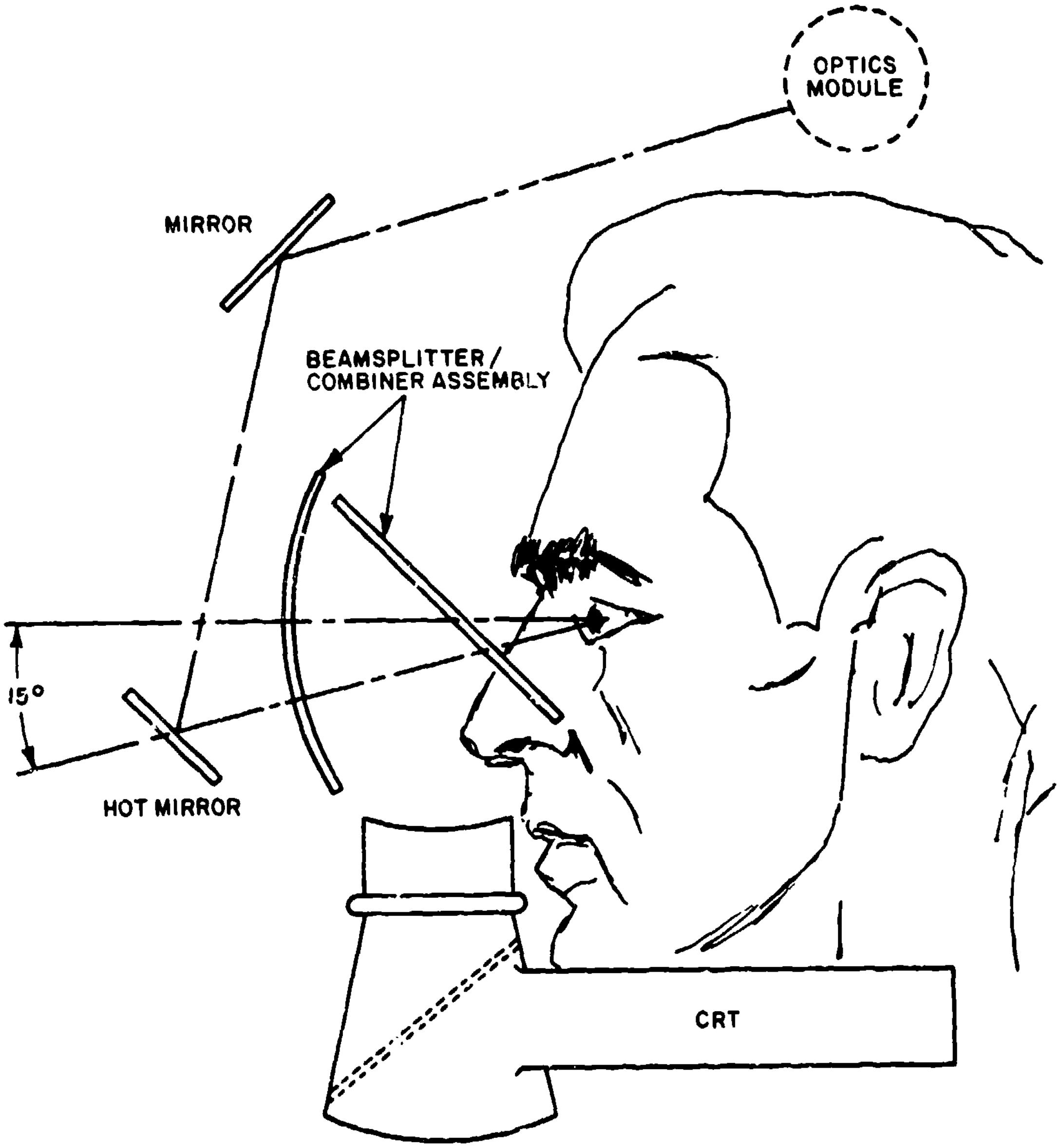

Figure 6.10 Possible eye tracker optical path for dual mirror VPD helmet.

the pilot's eye or eyebrow, followed by a second mirror, at the top of the cowling, to direct the image back over the forehead.

6.3 Sensor Selection

The most basic decision regarding the choice of a detector is whether to use a device that provides very complete spatial information, but requires a lot of processing, or a sensor that produces less complete information and carries a smaller processing burden. Different types of optical detectors were reviewed in section 5 of volume I

(Review of Current Eye Movement Measurement Technology). We feel strongly that the best sensor choice for a VPD eye tracker is a full two-dimensional array capable of producing grey scale information. This choice is driven by the need to achieve a high degree of dependability in an environment where imaging may often be less than ideal. Continuing advances in high speed digital processing are rapidly reducing the computational burden of dealing with large numbers of image elements.

If the image is collapsed onto linear arrays by cylindrical lenses or the equivalent, high spatial frequency information is irretrievably lost and a human readable image cannot easily be created. Other sensors provide even less complete information.

Commercially-available CCD cameras with miniature remote sense heads are appropriate for a 60 Hz version of the VPD eye tracker. A typical camera used in current ASL helmet mounted eye trackers has a 510 Horizontal x 492 Vertical pixel array (effectively 510 H x 246 V when used in a noninterlaced mode), has a sense head that measures 32 mm x 42 mm x 25 mm and a small electronics unit (32 mm x 42 mm x 118 mm) attached to the sense head by a flexible four foot cable. The remote sense head is small enough for helmet mounting and, by repackaging, can be made even smaller and lighter, if necessary. Similar devices with smaller sense heads will probably be commercially available in several months.

For a 120 Hz or 240 Hz version of the VPD eye tracker, an appropriate detector choice would be the Reticon MC9128 camera with a 128 x 128 pixel array. The full pixel array can be scanned at up to 300 Hz. A possible alternate choice is the CID Technologies, Inc. (formerly GE Intelligent Vision Systems Operation) CID2250. Although the CID techologies device is a 512 x 512 pixel array, at 240 Hz only 512 x 64 pixels can be used. EG&G Reticon supplies a 256 x 256 pixel device (Model M9256) but it also can update at over 100 Hz only by scanning a subset of the available lines. Since the eye cannot move very far in one sample period, one of these higher resolution devices could potentially be used to advantage by always scanning a subset of lines centered over the last pupil position. If the pupil is not found in this region, after a blink for example, one longer sample period would be required to scan the entire field. We estimate that 128 x 128 pixels will provide sufficient resolution and we would elect not to impose this additional complexity.

The EG&G Reticon M9128 device is not sold with a miniature sense head, and will have to be repackaged, as would any currently available high speed array. Before solid state cameras were commonly available with miniature sense heads, ASL re-engineered and miniaturized conventional 60 Hz solid state cameras for helmet mounting, and we are confident that this can be accomplished. It will also be necessary to design and build a controller to provide the necessary timing and control signals.

Increased update rate results in decreased camera integration time and causes a corresponding decrease in sensitivity. At ASL, we have, in

the past, produced useable bright pupil images with a Reticon M9128 operating at 200 Hz under laboratory conditions. We are confident that enough sensitivity can be achieved with this device at 240 Hz, even under operational conditions, for either bright or dark pupil use. It may be necessary to maximize sensitivity by thermoelectrically cooling the sensor chip to decrease dark current, and by correcting for individual pixel offset.

We recommend that a 60 Hz prototype system be developed first, allowing concentrated effort on the most important problem; specifically, robust recognition and center computation in the presence of artifacts and nonideal images. Enhancement to 240 Hz will require additional engineering as described above, but will not involve significant duplication of effort.

6.4 Algorithm

Current ASL pupil-to-CR eye trackers use size, shape, smoothness, and continuity criteria to recognize the pupil and corneal reflection in a video image of the eye. The recognition logic is capable of a very significant amount of artifact rejection, and has been used quite successfully under a wide range of conditions. It does, however, have limits imposed primarily by the amount of available information, and the speed of the processor used. The computer processor receives only edge information determined by thresholding over horizontal scan lines through the video image. Edges or portions of edges that do not cross the appropriate threshold boundary in a given video field are irretrievably lost.

The possibilities for recognition algorithms are significantly expanded if the entire grey scale video field is made available to the processor. Local searches using different threshold values and edge enhancement techniques can be used to extend incomplete information generated by initial thresholding. For example, when a smooth edge is prematurely truncated, an edge enhancement algorithm can be locally employed to see if the edge really continues. If a limbus edge is detected instead of the pupil edge, then an area larger than a "legal" pupil will be enclosed, and the local area within can be searched with a different threshold and with edge enhancement techniques to find the true pupil edge. It should be possible to significantly improve the robustness of pupil and CR recognition over current systems.

Initial edge information will still be generated with threshold techniques. Current systems require manual adjustment of thresholds. The VPD eye tracker system should choose threshold values automatically with a histogram technique.

Detection and recognition results in groups of pixels presumed to belong to the pupil and CR. The centers of the pupil and CR can usually be determined with a resolution and precision of one pixel or better as illustrated by the following algorithm. Assumes an untruncated circular pupil image. To compute horizontal center, average the end point positions of horizontal pixel lines included in the pupil. The lines

near vertical center contain more pixels, and should actually be weighted more heavily than those near the top or the bottom. If we simply do not include the top and bottom 15% of the pupil lines in the calculation, the remaining lines would have weights ranging only from 1.0 to .707 and the weighting function can be ignored. Vertical center can be computed by the same procedure with respect to vertical lines of pixels.

The resolution, i.e., the smallest possible change in the measurement, will be 1/n pixels, where n is the number of end points used. Since we have one pixel quantization, the true position of any given line has a uniform probability distribution between +0.5 pixels, and the rms error associated with each end point value will be on the order of 0.3 pixels. If we assume statistical independence between end point errors, the averaging process will reduce the rms error by $\sqrt{n}$ where n is number of end points used. The algorithm described would yield a pupil center computation with a resolution of 1/n pixels and a precision, defined by twice the rms error, of $2/\sqrt{n}$. This analysis considers only quantization errors, not video noise, physiological variability, and other error sources.

Eyelid truncation, corneal reflection occlusion of a pupil edge, and occlusions by other artifacts will have the effect of reducing the number of line end points available for the computation. For example, if the CR occludes one section of pupil edge at the lower right of the pupil, we can exclude from the horizontal center computation the horizontal lines passing through that section of the pupil edge. So that we do not bias the result if the pupil is actually a tilted elipse, we can also exclude a similar set of lines near the top of the pupil. If too few edge points would be left, symmetry considerations, interpolation, or a combination of these techniques can be used to fill in the missing edge data.

The computation measurement can be further improved with other techniques. Quantization errors can be further reduced by using grey scale information for interpolation. If an edge point along one horizontal line is at pixel n, meaning that pixel n is above a threshold value T and pixel n+1 is below the threshold, then edge position P can be defined as

$$P = n + \frac{T - v(n)}{v(n+1) - v(n)} \qquad (9)$$

where v(i) is video level of pixel i.

The measurement can also be improved by simple spatial filtering to smooth pupil edges and reduce both quantization errors and video noise errors.

The eye line-of-gaze measurement will be computed with the pupil-to-CR technique in approximately the central 40-degree diameter visual

field over which the CR can be detected. Beyond the central field-of-view, where a corneal reflection cannot be detected, the measurement mode will switch and eye position will be determined by pupil center only. Measurement, with only the pupil, has the disadvantage of being affected by helmet slippage, and this problem is handled as follows. Whenever both pupil and corneal reflection are visible, a slip or correction factor is computed to "reset" the pupil center and "recalibrate" the pupil map. Since helmet slippage is a relatively infrequent phenomenon, this correction has been found to be satisfactory and is used by current ASL helmet-mounted eye trackers.

An alternate or supplementary technique is the use of pupil ellipticity calculation at eccentric eye positions. The pupil technique is not subject to helmet slip error, but requires substantially more computation and will not be used unless necessary.

6.5 Calibration

Although we know the underlying relationship between the pupil-to-CR vector and eye line-of-gaze (see section 4.5.1 of volume I), empirical data are required to correct for individual subject differences. The required data are gathered during a "calibration" procedure which, to ensure maximum accuracy, must be performed for every subject. We suggest that calibration computations employ a polynomial curve fit technique similar to that used by current ASL eye tracking systems (ref. 37), which will probably require about 17 target points spread over the visual field of interest. Interpolation techniques would require significantly more target points to achieve comparable accuracy over the large VPD range and would result in too lengthy a calibraton procedure.

The suggested protocol for pilot self calibration is as follows:

1. Pilot requests calibration procedure with a manual switch or voice command.

2. The VPD displays one target point.

3. The pilot fixates the target point and activates a manual switch while fixating the target.

4. If the eye tracker did not have proper eye recognition when the data entry switch was activated, an appropriate message is displayed so the pilot will know to try again or take corrective action.

5. If the eye tracker did have proper recognition, then the next target point is displayed and step 3 is repeated.

6. After the last target point is entered and calibration computations completed by the eye tracker, point-of-gaze feedback (SVFB) is displayed along with all target points so that the pilot can check performance.

7. Another switch activation by the pilot will end the calibration procedure.

6.6 Processor

The processor design objectives are to make as much image information as possible available for detection, recognition, and center computation algorithms, while providing enough computational power to achieve desired temporal resolution. The processing system architecture should be appropriate for 240 Hz operation, as well as for a 60 Hz prototype.

Considering the first objective, it is desirable to have entire grey scale images available in an image memory. It may, however, take too much time to access all of these pixels from image memory in order to find the image features of interest. We will, therefore, plan to use a preprocessor to perform threshold edge detection and histogram computation tasks "on the fly" as the video data comes from the camera. The main processor can quickly determine probable locations of important features from the edge information and, when necessary, sections of the raw image memory can be accessed for more detailed local processing.

A possible high speed (up to 240 Hz) design based on the VME bus and Motorola 68020 processor is diagrammed in figure 6.11. The camera controller as discussed in section 6.3 will be responsible for synchronizing to an external signal from the host, providing drive signals to the camera, and passing video data to the A/D converter. A 60 Hz prototype version of the eye tracker will differ from figure 6.11 only in that a more conventional 60 Hz CCD camera will be used in place of the Reticon M9128, and the custom camera controller can be replaced with a standard video sync signal generator and genlock circuit.

The front end processor (or preprocessor) will perform computationally intensive operations on the A/D output data "on the fly" and store the results in memory. Specifically, the processor will store the entire image in memory and will also store addresses of threshold crossing points, the address of the brightest pixel or pixels in the image, and intensity histogram data. The edge information is comparable to the image data available to current eye tracker processors. The raw image memory will significantly enhance the capabilities for feature detection and recognition. Histogram information can be used by the main processor to determine threshold values for subsequent fields.

The main processor, shown in figure 6.11 as a Motorola 68020, will be responsible for most feature recognition, eye position computation and communication with the host VPD system. Benchmark comparisons with the processor currently used for ASL eye trackers have shown a 7.5 times speed advantage for the 68020, and this may be sufficient for the higher speed and increased computations needed.

If a single 68020 processor is not sufficient, a special purpose high speed processor, as shown in figure 6.11, can be included and used for computationally-intensive portions of the algorithm. Such a

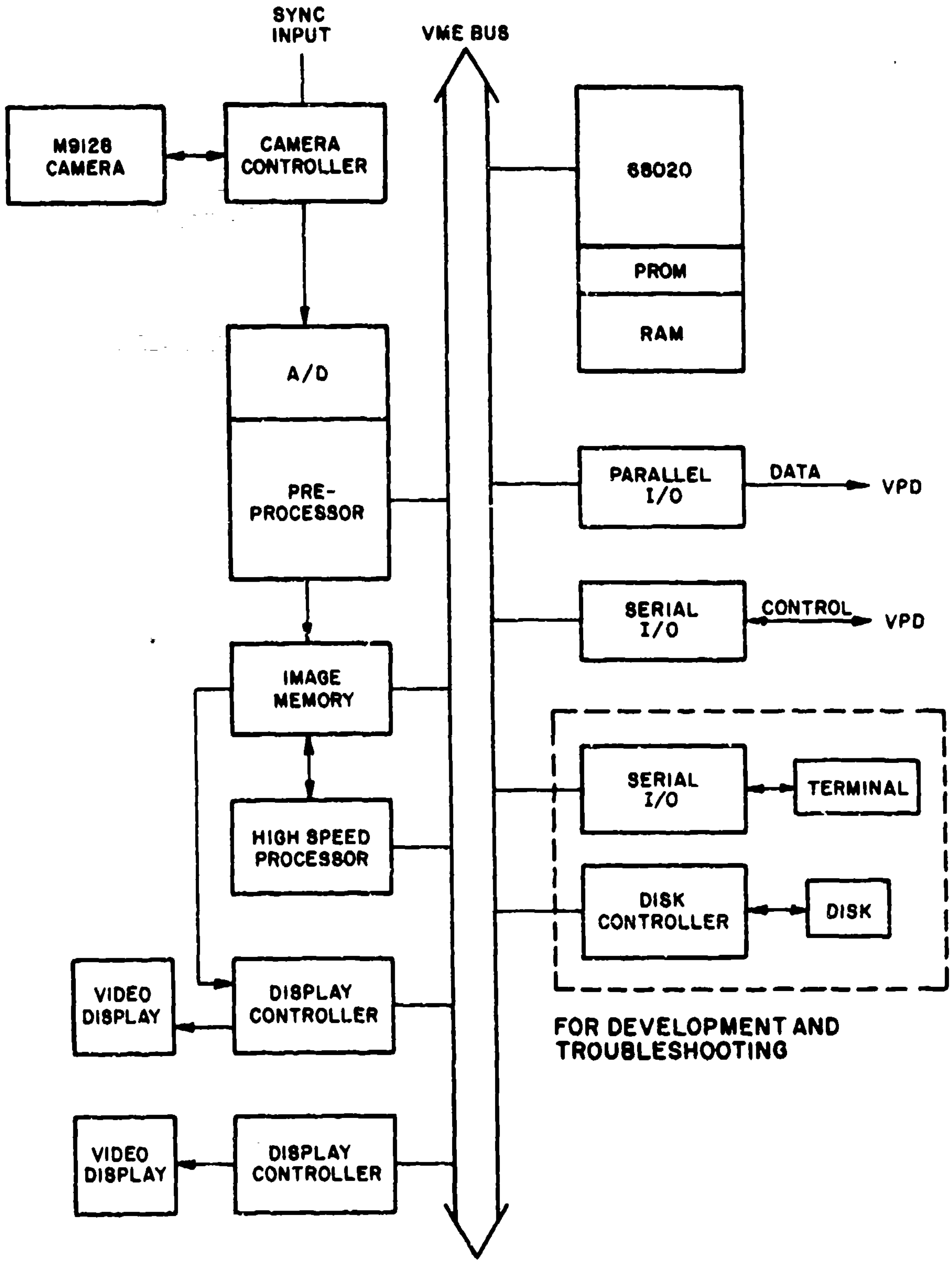

Figure 6.11 Processing system for VPD eye tracker.

processor, for example a 40 MIPS, bit slice level device, will definitely provide the necessary computational power, but should be used very sparingly because of the high overhead associated with the microcode programming that these devices require. To the extent that algorithm functions can be implemented in parallel, processing power can also be enhanced by adding an additional 68020 module to the VME bus. The hardware used should be the minimum required for the computational task and these specific decisions can be made most effectively after the algorithm is successfully tested off-line.

Data will be transferred to the VPD host system through a parallel port compatible with the appropriate Q22 or Unibus interface. Each data field will be composed of 5 words, as listed below:

1. Eye azimuth position

2. Eye elevation position

3. Pupil diameter

4. Status (error conditions, etc.)

5. Check sum (sum of previous 4 words to check for transmission errors)

The eye tracker will also be interfaced to the VPD host through a standard RS232 serial port from which the host will be able to initiate and control the calibration sequence, request offset corrections, etc.

It is very important, especially during initial phases of simulator research, that sufficient feedback be available to qualitatively evaluate eye tracker performance in real-time and to understand the nature of any problems encountered. For this reason, two displays are shown in figure 6.11. One display will be the video eye image captured by the detector with indicators superimposed to show system recognition and center computation. A second display will show the resulting line-of-gaze computation as a cursor or cross hair moving over the visual field.

The eye tracker transport delay will probably be three fields (update intervals) as shown by the timing diagram in figure 6.12. If the main processor completes computations in less than one field, the delay may be slightly shorter, but will always be greater than two fields.

Nothing in the processing system proposed is beyond current state-of-the-art, and most components are commercially available. The camera controller for high speed (240 Hz) operation and the front end processor will be custom components. Some of the non-VME bus interfaces between components may also be custom designed. Motorola 68000 series CPU and floating point processor combinations have been developed for programs requiring in-flight use with other VPD systems and other AAMRL developments, and thus meet appropriate mil-spec requirements for

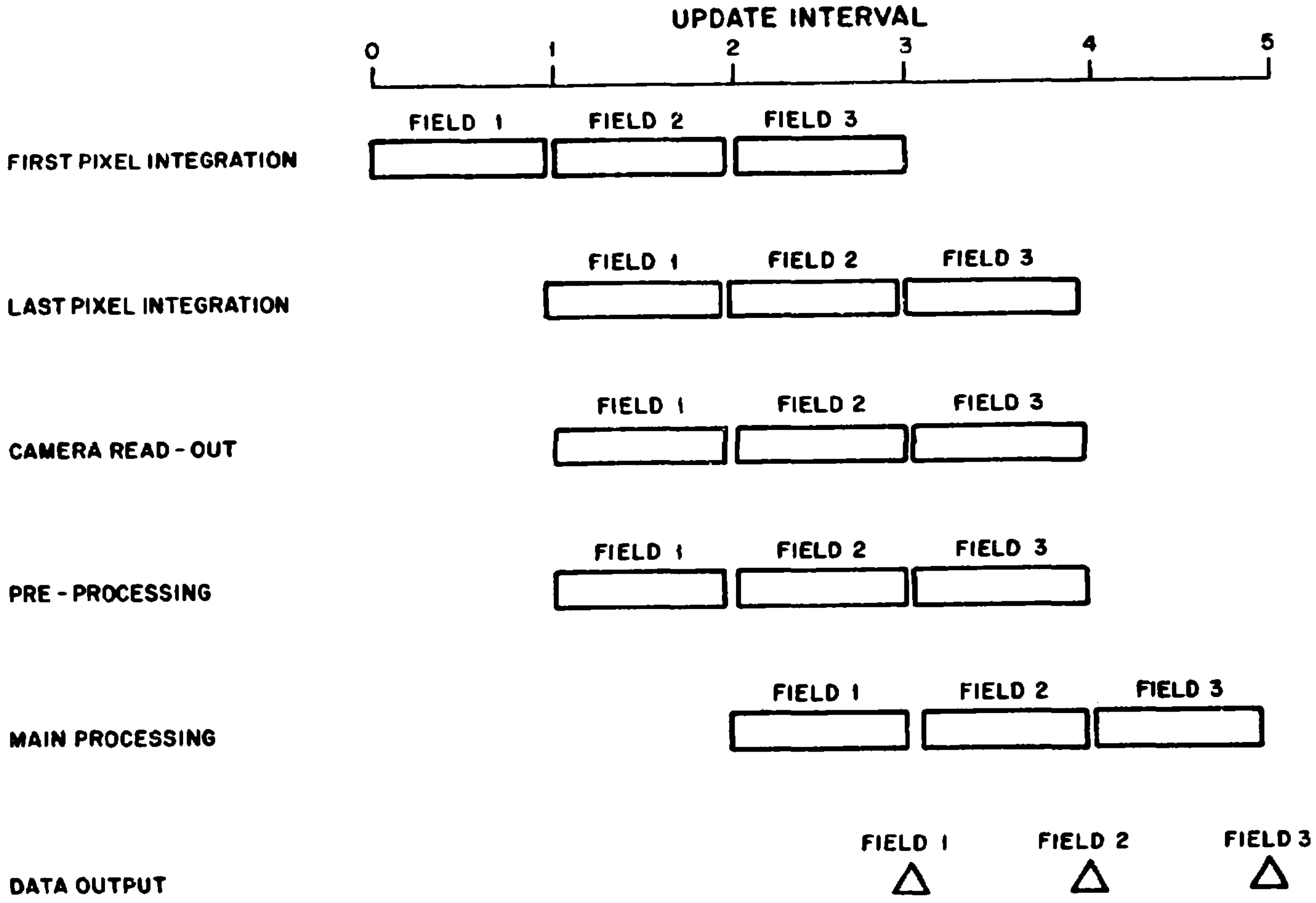

Figure 6.12 Eye tracker timing diagram.

flight. When detailed specifications become available, these processors should be evaluated and considered for a VPD eye tracker.

The VME bus and 68020 processor were chosen for consistency with other VPD components and because VME is a reasonably fast bus that has become something of an industrial standard. The same design framework would be possible using an Intel 80386 processor and an IBM bus. Because the IBM bus is relatively slow, the image memory would probably have to be interfaced directly to the high speed port available on the 80386 processor, and an IBM bus design would not be consistent with other VPD components. There may, however, be some advantage to IBM in terms of component cost, variety of commercially available components, and variety of available software development tools.

The algorithm can be developed and tested off-line using digitally stored images. An off-line development system must include a processor, a hard disk, a video frame grabber, a display terminal and suitable software development tools. One of the standard 80286 or 80386 based systems now available, plus an added frame grabber, would be sufficient for this task. This class of system offers the advantages of relatively low cost, a large quantity and variety of compatible frame grabber boards, and most importantly, an enormous number of excellent software development tools which will significantly facilitate the algorithm development task.

6.7 Performance Goals

The following specifications represent reasonable performance goals for the VPD eye tracker. Although not exactly the same as the ideal specifications listed in 5.7, the most important aspects are preserved and the goals are realistic.

Inner Tracking Range:	$\pm$20 deg vertical and horizontal
Outer Tracking Range:	field between inner and total range
Accuracy:	0.7 deg within inner range 2.5 deg within outer range
Precision:	0.35 deg
Resolution:	0.25 deg
Update Rate:	60 Hz -- first prototype 240 Hz -- enhanced prototype
Transport Delay:	3 update intervals
Pupil Diameter Range:	2-8 mm

Total Eye Tracking Range:	+40 deg horizontal; +30 deg (up) -25 deg (down) vertical
Optics Adjustment:	requires 1 minute or less after VPD helmet donned
Calibration Procedure:	- requires 1 min or less - can be self administered by pilot - quick offset adjustment capability after calibration
Tolerance for Helmet Slippage:	4 mm at the eye

Perhaps the most important performance goal can best be stated qualitatively: the system must perform dependably with the nonideal images and artifacts that will often be present in a complex environment like the VPD. These "real world" considerations are the driving force behind the design approaches outlined in the preceding sections and the development program outlined in the following section.

7.0 VPD EYE TRACKER DEVELOPMENT PROGRAM

A logical sequence of tasks for a VPD eye tracker development program is presented below.

1. Obtain detailed dimensions and optical specifications for the VPD design to be used.

2. Build bright and dark pupil breadboard optics packages to test with a prototype VPD helmet using one of the optical path approaches discussed in section 6.2. The breadboard package should include an illuminator, standard 60 Hz solid state video camera, and necessary relay optics. Components need not be packaged nor need they be rigidly fastened to the helmet, but rather the helmet can be stabilized in some way (e.g., subject chin rest) and components held by lab stands or temporarily fastened to the helmet.

3. Using real subjects, experiment with the breadboard optics to obtain the most suitable camera eye image. These tests should be done both with the VPD display projector off and with the display on. When the display is on, tests should be done with the full range of scene luminance levels likely to be experienced in actual use. If the prototype system is to be used in flight, then daylight conditions should be tested as well.

4. Video tape the resulting eye camera images and, if possible, use a computer and video frame grabber to digitally record some

of the images. It will be important to collect images at a wide range of eye positions and images exhibiting samples of all expected artifacts.

5. If necessary, revise the optics breadboards and repeat step 3 and 4.

6. In parallel with steps 1 through 5, set up a development system for off-line work on the eye tracker algorithms. As discussed in section 6.5, this system must include a processor, a hard disk, a video frame grabber, a display terminal, and suitable software development tools.

7. Digitize selected images from video tape data collected in steps 3 through 5 and use the data to develop and test pupil and CR recognition and center computation algorithms.

   From an algorithmic point of view, the difference between the 60 Hz image and future higher sample rate images will be lower spatial resolution of the high speed images (i.e., detectors with fewer pixels). Lower spatial resolution can easily be simulated by mathematically combining neighboring pixel values. Algorithms should be tested with simulated 128 x 128 pixel resolution, as well as with full resolution.

8. Based on the results of step 7 and the framework presented in section 6.5, decide whether to use bright or dark pupil optics and specify the real time processing system for a prototype VPD eye tracker. Although it is suggested that the first prototype be a 60 Hz system, the processing system should be suitable for up to 240 Hz operation.

9. Implement the processor design specified in step 8.

10. In parallel with step 9, specify the final optics module design for the 60 Hz version prototype system and construct a "brassboard" version.

11. Test the optics module brassboard with the VPD system, revise if necessary, and construct the final optics module for the 60 Hz prototype eye tracker.

12. Test the completed processor system.

13. Test the combined optics and processor system in real time.

14. Deliver the 60 Hz prototype VPD eye tracker and test with the prototype VPD system.

15. Develop high speed camera controller, high speed detector repackaging, and optics module modifications for high speed enhancement to VPD eye tracker.

16. Test breadboard versions of high speed components.

17. Deliver and install enhancements for 240 Hz eye tracker operation.

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